SIMULATION BASED PERFORMANCE EVALUATION OF RESOURCE ALLOCATION ALGORITHMS FOR IMPLEMENTATION IN THE SHF-DAMA SATELLITE NETWORK

THESIS

Eric P. Hobson, Captain, USAF

AFIT/GCS/ENG/96D-10

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GCS/ENG/96D-10

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THESIS

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Eric P. Hobson, B.S.

Captain, USAF

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Eric P. Hobson

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Abstract

Sponsored by DISA, the SHF-DAMA Standard addresses the warfighter's requirements for flexible, reliable, and efficient (technically and fiscally) satellite communications. The Standard proposes a system supporting both packet data transfer and single-channel-per-carrier voice and data circuits assigned on a demand basis. The Standard does not address management of the DSCS III transponder's bandwidth and power resources among priority classes of users.

This effort characterizes the SHF-DAMA system's performance over each combination of the following resource management algorithm features: preemption enabled and disabled; using the Standard-specified collision resolution technique and a binary exponential backoff; using complete partitioning, complete sharing, and sharing with minimum allocation strategies. The author introduces a novel algorithm for avoiding unnecessary preemption. A simulation written in MODSIM II collects the following measures of performance over a broad load range: call establishment delay, number of calls simultaneously supported, power used, and number of calls preempted.

The primary conclusion drawn using graphical and hypothesis testing methods is that the SHF-DAMA system should implement the complete sharing management algorithm. This algorithm reduces call setup time and most efficiently manages satellite resources. As a secondary conclusion, the binary exponential backoff proves to be not significantly better than the Standard-specified backoff.

SIMULATION BASED PERFORMANCE EVALUATION OF RESOURCE ALLOCATION ALGORITHMS FOR IMPLEMENTATION IN THE SHF-DAMA SATELLITE NETWORK

1. Introduction

In modern warfare commanders require timely, accurate information as much as accurate weapons. The growing need for information and the increasing pressure from an increasingly crowded frequency spectrum demand more efficient use of available spectrum. Unlike many commercial systems, military systems must provide global service to dynamically changing traffic types at widely varying utilization levels. As budgets decline and force levels draw down, these systems must reduce expenditures and include the capability of mostly autonomous management. What type of inexpensive system simultaneously utilizes bandwidth efficiently, handles traffic dynamics, and mostly manages itself? The Super High Frequency Demand Assigned Multiple Access (SHF-DAMA) Standard addresses these issues. The Defense Information Systems Agency (DISA) sponsors the SHF-DAMA Standard development effort.

1.1 Research Goals

This work investigates the potential performance of the proposed SHF-DAMA system. Limited to considering direct network terminal (NT)-to-NT single-channel-per-carrier traffic, this work presents the call establishment delay, power usage, number of calls connected and preempted over a range of load and resource allocation algorithms. The central network control terminal implements a complete sharing, complete partitioning, and sharing with minimum allocation algorithms to manage the transponder's power and bandwidth resources.

Results from computer simulation of the system are used to make a recommendation as to the allocation algorithm best suited for implementation in the SHF-DAMA system.

1.2 Document Organization

Chapter 2 presents, in a stepwise refinement process, the SHF-DAMA standard and relevant background in the area of multiple access communications. The discussion starts with root communications concepts followed by an overview of multiple access techniques. These techniques are then refined and contrasted. Attention then focuses on single-channel-per-carrier modulation and the centralized demand-assigned multiple access (DAMA) protocol. Finally, the SHF-DAMA standard is presented in light of prior discussions.

Chapter 3 builds on the previous chapter's background, and focuses on the study itself. Following a restatement of the problem, the limitations and assumptions of the effort are explored. The approach to the investigation is then stepped through, including

the model description and processes to be followed. Alternatives are then examined, expected results proposed and satisfaction criteria delineated.

Chapter 4 presents details of the experiment design, conduct, and results. Summary data are presented with full details in the appendices.

Chapter 5 summarizes this effort, restates conclusions from Chapter 4, highlights contributions of this work and outlines areas for further research.

2. Background

2.1 Introduction

In a stepwise refinement process, this chapter presents the SHF-DAMA standard and relevant background in the area of multiple access communications. Accordingly, the discussion starts with root communications concepts followed by an overview of multiple access techniques. These techniques are then refined and contrasted. Attention then focuses on single-channel-per-carrier modulation and the centralized demand-assigned multiple access (DAMA) protocol. Finally, the SHF- DAMA standard is presented in light of prior discussions.

2.2 Communications Basics--The Channel

In the most generic terms, a communications system consists of two or more devices (telephones, computers, facsimile machines, etc.) exchanging data over some medium. Typically this medium (phone line, coaxial cable, microwave beam, etc.) may support more than one pair of users' requirements. To make efficient use of the expensive transmission medium, therefore, users share the medium by some mechanism. For the remainder of this document, the terms *link* or *circuit* denote the transmission path effected by some medium and the term *channel* refers to the fraction of a circuit allocated to a user [Sta91].

2.3 Satellite System Basics

Communications satellite systems consist of three main components: the earth terminals (known also as ground terminals) the space segment (satellite itself), and control functions. Each of these performs important duties.

Ground terminals act as access points to the communications network. These terminals may support a single channel, as in a portable satellite telephone, or may interface the satellite network to some other data system (e.g., a local area network). Overall, the satellite system effects communications between the ground terminals--not the users' data systems. To accomplish this, terminals encode and translate the incoming data (baseband communication) to microwave frequency for transmission to the satellite. The satellite receives the (degraded) signal, translates the signal to a different frequency and re-radiates it back down to all the ground terminals (so-called bent pipe). Note that in this simple arrangement, all ground terminals receive all transmissions (including their own), thus effecting a broadcast mechanism. The actual satellite component supporting this signal relay is called a transponder, for "translator + responder." The transponder takes a signal at the uplink frequency, amplifies it, and transmits it at a different, downlink frequency. A single satellite typically possesses many transponders, one for each portion of the overall frequency band supported.

Satellite systems differ from their terrestrial counterparts primarily because the altitude of the satellite, in particular a geostationary satellite, results in long propagation delays between ground terminals. Usually a value of 0.25 sec suffices for estimating this delay [SaA94]. Somewhat similar to radio systems, the ground terminals carefully adjust

transmit power levels to assure adequate reception at other terminals while not overpowering another terminal's transmission.

The satellite systems' control segment monitors and maintains the health and status of the space segment, and manages the information flow through the system. Typically, different facilities and staffs support these distinct functions.

2.4 Multiple Access: Why, What, and How

2.4.1 What and Why: Link Division for Efficient Use of Transponders

As seen in the previous section, a link likely supports more than one channel. This is particularly true for satellite systems, where links operate with bandwidths (useable frequency ranges) of many megahertz (MHz), while, for example, a voice circuit requires only 4 KHz [Sta91, Rai96] . Thus, terminals must implement some means of sharing the enormously expensive satellite system capacity.

2.4.2 Classification of Multiple Access Protocols: How

The physical means of dividing the link and the algorithm used to assign channels to links provide a taxonomy of multiple access protocols. Both of these directly affect the suitability of a protocol for a particular application.

2.4.2.1 Partitioning the Physical Link: What--FDMA/SCPC, TDMA, and CDMA

Viewing the link as simply electromagnetic waves from some continuous range of frequencies, multiple channels share the link in either the frequency or time domain. *Frequency division multiple access* (FDMA) divides the link's range of frequencies into non-overlapping segments, each channel/terminal getting to use one. The terminal uses

data multiplexed from user equipment to modulate a carrier centered within its assigned frequencies. Thus each channel (of multiplexed and modulated data) gets a fraction of the link's capacity, but may transmit continuously. Related to FDMA, single-channel-per-carrier (SCPC) techniques do not multiplex data to a single carrier. Rather, each user data source occupies a channel, modulating a single, separate carrier.

In contrast to this, *time division multiple access* (TDMA) divides the link in the time domain. A (perhaps variable) number of these slots constitute a frame. Channels take turns using the full link bandwidth by using a subset of the slots in successive frames. Note that this requires tight timing coordination between channels, and therefore terminals.

Code division multiple access (CDMA) combines TDMA and FDMA. This technique divides the frequency band of the link into frequency bins. Each channel hops frequencies on an assigned pattern so that multiple channels infrequently use the same frequency (collide). Channel transmissions include additional error correcting information so that these collisions necessitate few retransmissions [SaA94]. The system under consideration in this project does not use CDMA. As such, CDMA receives no further attention. Figure 1 depicts CDMA as well as FDMA and TDMA.

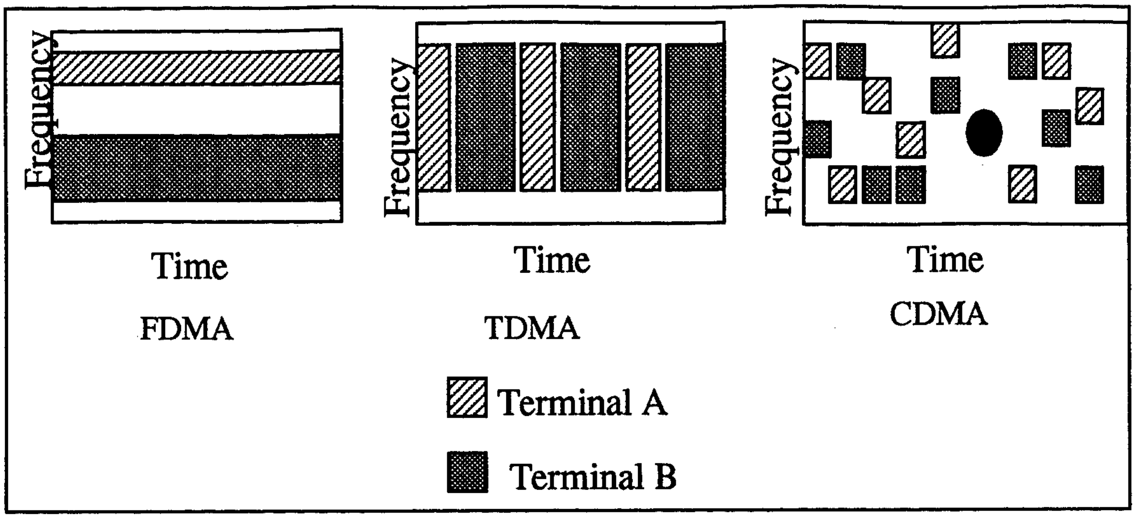

Figure 1. Link Division Categories.

2.4.2.2 Channel Access Method: How

From the preceding section, we see that aside from the time versus frequency distinction, "a channel is a channel is a channel." The other aspect of a multiple access protocol is how the terminal obtains and uses channels. Planned, random, or a hybrid techniques may assign channels to link partitions.

2.4.2.2.1 Deterministic Link Access

Deterministic link access divides the link into channels such that no two channels access the link portion simultaneously. This can be done in two ways: by fixing assignments once and for all, or by dynamically allocating channels by some centralized or decentralized entity.

Using fixed assignment, each channel receives a static portion of the link. Thus for FDMA, the channel receives a fixed carrier frequency and bandwidth while a TDMA channel receives a fixed set of time slots. System designers calculate once and for all how much of the link each channel requires.

Dynamic channel assignment is realized via either a central mechanism or a distributed algorithm executed by each of the terminals. Polling illustrates centralized allocation [SaA94]. A central agent interrogates each terminal whether it has data to send and gives it permission to do so. Probing exemplifies distributed allocation. In probing, the terminals themselves coordinate access by means of a token passing technique. By passing a token to the next terminal, a terminal effectively polls the next terminal. Local area networks successfully use this technique [SaA94].

2.4.2.2.2 Random Link Access--The ALOHA Protocols

Unlike deterministic techniques, random channel assignments follow no predetermined pattern. In the simplest random technique, the ALOHA protocol, channels use the link whenever they have data to send. Because a terminal monitors its own transmission via the downlink, it determines whether or not its transmission succeeded. It reschedules unsuccessful transmissions according to a random backoff.

A variant of this technique is Slotted ALOHA (S-ALOHA). Using this technique, the link is accessed only at fixed time intervals, similar to time division multiple access. If a terminal has data to transmit, it waits until the beginning of the next available slot and transmits. Again, it monitors the downlink to see if the transmission succeeded and reschedules data for retransmission upon a collision. As we will see, this method has advantages over pure ALOHA.

2.4.2.2.3 Hybrid Link Access--DAMA and Adaptive Techniques

Depending on the traffic characteristics and equipment complexity, a mix of random and deterministic link access may be appropriate. The allocation of channel resources may by done by a distributed algorithm or a central agent, and may require explicit or implicit reservations [NgS90].

Reservation ALOHA (R-ALOHA) is a form of TDMA demand-assigned multiple access (DAMA). Like S-ALOHA, channels compete for access to a TDMA link. Unlike S-ALOHA, however, once a terminal successfully competes for a slot, it maintains the right to transmit in that slot in future frames. Each terminal maintains a table of what slots are available. In this way the terminal can be assured of future link usage. This is an example of a distributed assignment, implicit reservation algorithm. A similar distributed assignment, explicit reservation system is ALOHA-Reservation, in which the terminal competes for channel allocation for each transmission [NgS90].

Central control of channel assignments denotes another DAMA system. When used for satellite communications, the terminals submit requests for channels via S-ALOHA over a dedicated channel, or possibly designated slots in a TDMA system. A central controller examines requests, assigns link accesses or prepares a message that the request is blocked, and broadcasts a response [RaB80]. Terminals then schedule their transmissions for the frequencies (FDMA/SCPC) or slots (TDMA) assigned by the controller. The controller may require reservation for each terminal transmission or allow multiple transmissions.

The PODA protocol combines DAMA and random access techniques [NgS90]. In this TDM-based protocol, a frame consists of a variable number of reservation slots and data slots. These slots increase or decrease in proportion to the demand [Abr92, SaA94, NgS90, Sta91].

2.4.3 Problems Introduced/Performance Measures

Although multiple access techniques provide for the possibility of better link utilization, many factors contribute to an overall judgment of performance. These judgments depend on the traffic supported and typically include the following measures of performance: [SaA94, Bin81]

- Average throughput.
- Delay (of packets through the system or of circuit establishment).
- Link utilization.
- Stability of the network.
- Ability to support circuit and message traffic and ability to support variable length messages.
- Ability to implement priorities.
- Fairness in channel allocations.
- Flexibility to changes in the number of terminals.
- System complexity.

2.5 Traffic Modeling

Traffic can be broadly classified as synchronous and isynchronous, or asynchronous [AiB90]. Voice and video transmission illustrate synchronous and isynchronous data, respectively. In general, these classes have tight timing requirements and must be

implemented by a (virtual) circuit [AiB90]. Asynchronous traffic consist of bursty packet data.

Analytic examinations almost universally model both types of data as infinite populations producing a Poisson arrival process with exponential holding times, although this is overly restrictive. Useful results can be derived whenever the holding time (call length or packet length) has a rational Laplace transform [Kau81]. Chapter Three discusses the traffic model in much more detail, as does the last section of this chapter.

2.6 Multiple Access Technique Comparison

This section examines the multiple access techniques presented in light of many of the performance criteria and the traffic model above. In particular, each technique is examined according to its delay characteristics, susceptibility to noise, and system flexibility and complexity. In turn, these factors give rise to indications about the technique's suitability for circuit or message traffic.

2.6.1 TDMA Versus FDMA

Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) present some tradeoffs without regard to the channel allocation mechanism (deterministic versus random versus hybrid access). Some of these tradeoffs, however, refer to the suitability for implementation in one of these three access techniques which themselves have tradeoffs. Correspondingly, this section introduces TDMA versus FDMA in as pristine a comparison as possible, while acknowledging that other factors warrant consideration.

While standard FDMA (static assignments) maintains a relatively simple technique, it suffers greatly in terms of flexibility and efficiency. System control is simple as each terminal transmits only on a single carrier. Because each terminal uses a different carrier, however, each must simultaneously receive all transmitted carriers to receive from all terminals [Qua77]. Due to its rigid channel assignments, FDMA cannot adapt to changing loads or network topologies [Qua77, ScF84]. Finally, nonlinearities in the transponder mark FDMA as highly susceptible to intermodulation noise [ScF84, Qua77, Sta91]. Correspondingly, utilization of the transponder suffers; for example, from being able to support 1200 voice channels for a single carrier down to only 500 using multiple carriers [Qua77].

Because time division multiple access transmission uses only one carrier, TDMA does not suffer from FDMA's intermodulation noise limitation [ScF84]. This permits operating the transponder (amplifier) closer to its saturation point. Since terminals can then transmit at a lower power, they are smaller and less expensive. Note, however, that terminal complexity increases from the strict timing coordination requirement imposed by TDMA's slotted access. Similar to FDMA, standard TDMA suffers from its rigid assignments.

Although single-channel-per-carrier (SCPC) transmission does not by itself rectify the deficiencies of FDMA, it allows for adaptations that do. Since a terminal does not multiplex data to a common carrier, the terminal may be simpler. Counter to this, however, a terminal must simultaneously transmit and receive on many frequencies to achieve reasonable network connectivity. Provided a large enough selection of

transmitting and receiving frequencies, intermodulation effects still present problems, although they are manageable ones.

2.6.2 *Fixed Assignment Techniques*

The fixed assignments technique provides the basic architecture of FDMA and TDMA as presented above. The simplest multiple access technique, fixed assignment, works well for heavy traffic loads.

In terms of control complexity and channel access delays, the fixed assignment technique is ideal [NgS90]. The control consists of assigning the channels during system design and never changing them. Because each channel operates independently, the terminal may use its channel at any time without any access delay. Thus the total delay in a fixed technique is one hop--one uplink and one downlink delay, again about 0.25 seconds.

If a terminal consistently concentrates sufficient traffic from its sources, the fixed assignment technique results in reasonable link utilization. Usually this is not case. Particularly for bursty packet traffic, a great deal of channel capacity lies unused [Abr92, Bin81, JoR88].

Finally, fixing channel assignments results in a system completely incapable of adapting to changing number of terminals or traffic at any terminal [Bin81]. Also, since each terminal gets a dedicated portion of the available bandwidth, a great deal of bandwidth is required. Even for TDMA, increasing the number of terminals requires lengthening the frame, resulting in unacceptable delays for circuit traffic [NgS90]. Alternatively, adjusting to a faster bit rate would solve TDMA's problem, but this requires

more bandwidth. Because of limited available bandwidth, the fixed assignment techniques support only networks of very few terminals [Abr92]. This severely limits their suitability for Very Small Aperture Terminal (VSAT) applications [Abr92]. Rather, their application lies in television and trunking telephone applications.

2.6.3 Random Assignment Techniques

To counter the limitations of the fixed assignment technique, multiple channels must share a link. The simplest mechanism for this is a *contention protocol*--a technique where terminals compete for access to the link. ALOHA and S-ALOHA form the root of such protocols. These simple techniques trade low access delay for low utilization.

An ALOHA channel can be viewed as a feedback system [SaA94]. The channel carries new transmissions and retransmissions of previously collided packets. As load increases the number of retransmissions also increases, with the ultimate result being that no packets transmissions succeed, resulting in instability. Well known statistics include a maximum link utilization of about 18% for ALOHA and 37% for S-ALOHA [NgS90, SaA94, Sta91].

To increase the utilization level of ALOHA-based protocols, preference must be given to some traffic. In ALOHA with capture, some terminals transmit at a low power and others at a higher power. A transmission will succeed if only one low power terminal transmits, or only one high power terminal transmits and any number of low power terminals transmit. The high power terminal's signal will override signal of the low power terminals. Techniques implementing two levels realize up to 53% utilization [SaA94]. Low power terminals experience more collisions and receive a lower grade of service,

however. Also, for a single level ALOHA system, utilization can approach 100% if a single terminal transmits close to full time. Again this subordinates other terminals' access to the link.

Given that collided packets must be retransmitted, at an additional one-hop delay, ALOHA and its derivatives are not suitable for circuit (voice, video) services [NgS90]. Rather, its usefulness lies with low-load packet traffic [NgS90].

2.6.4 Deterministic Technique--Polling and Probing

Although they do eliminate collisions, polling and probing should never be used in geosynchronous satellite systems. In both cases, a minimum 0.25 sec period elapses between station accesses. In this lag, no data is transferred, thus clearly wasting capacity [Sta91].

2.6.5 Hybrid Techniques--DAMA

Fixed assignment techniques lack flexibility and random assignment techniques lack high throughput, stability, and the ability to support circuit and packet traffic. Demand-assigned multiple access (DAMA) techniques alleviates these problems. As mentioned earlier, DAMA may be implemented via a distributed algorithm executed by every terminal or by a central controller, and may require explicit or allow implicit reservations [NgS90]. In general, DAMA permits a greater throughput but results in longer delays, particularly for data traffic, and increases implementation complexity [McJ85].

2.6.5.1 *Central Control DAMA*

Central control requires terminals to use a dedicated ALOHA or S-ALOHA type request channel (or dedicated slots of a main channel) to communicate requests to a central resource controller [RaB80]. The controller executes a scheduling algorithm and responds via a common channel with channel assignments or messages that the channel cannot be established [Abr92, RaB80]. The central controller may implement traffic priorities.

The assignment request opportunities may be assigned or contended for. The INTELSAT SPADE and Indonesian PALPA systems used fixed allocations of request opportunities whereas the INMARSAT system first used a contention channel in a commercial system [Abr92]. As with FDMA and TDMA, fixing the request opportunities severely limits system flexibility [Abr92].

Central control DAMA's hub architecture allows for simpler terminals. The terminals send packet traffic (and in some cases circuit traffic as well) to the central hub for rebroadcasting. Because a central terminal likely has more transmission power capacity, the remote terminals can transmit at a lower power, reducing their complexity [Abr92]. This hub architecture results in a single point of failure, so a backup hub may need to be kept ready [Lab85].

Because a central controller has perfect knowledge of traffic requirements, central control DAMA's efficiency can theoretically reach that of a perfect concentrator at the expense of the reservation channel [McJ85]. Note that since a terminal must wait for permission from a central controller to transmit, the minimum delay is two round trips

(one or reservation, one for permit), as opposed to decentralized DAMA, where the minimum delay is one round trip [NgS90, Sta91]. For contention-based DAMA reservations, delays occur from accessing the reservation channel or queueing at the controller. These delays lead to the additional performance measures of reservation channel throughput and data channel utilization [JoR88].

2.6.5.2 Distributed DAMA

Unlike centralized DAMA, each terminal executes a scheduling algorithm. This greatly increases the complexity of the terminals but results in a one-hop delay for channel assignments instead of a two-hop delay [NgS90, Sta91]. Because each terminal must have the same view of global traffic requirements, distributed DAMA is more vulnerable to loss of synchronization [Sta91]. Both explicit reservation and implicit reservation techniques have been studied.

PODA, R-ALOHA, and Binder's algorithm all allow implicit reservations [Bin81, Sta91]. R-ALOHA allows all assignment opportunities to be contended for while Binder's algorithm assures a terminal access to some channel capacity, thus better serving circuit traffic [Bin81, Sta91]. PODA allows explicit reservation for datagrams, batches of datagrams, or an entire stream, and can implement priorities [Bin81, Sta91]. Thus PODA serves a wide variety of traffic types well.

2.7 SCPC and DAMA

This section highlights the potential benefits of dividing the physical link via single-channel-per-carrier (SCPC) techniques and assigning the resultant channels with demand-assigned multiple access (DAMA).

2.7.1 SCPC Review

SCPC involves dividing the frequency spectrum into channels capable of supporting a simplex channel. Duplex channels are implemented by allocating a channel in both directions. The SPADE system allocated channels in blocks of 45-KHz: a 38-KHz QPSK signal for carrying PCM encoded voice and a 7-KHz guard band [ScF84, Sta91]. SCPC allows carrier power to be adjusted, either to conserve overall transponder power or to effect a multilevel communications system [HoL79].

2.7.2 Advantages Over FDMA and TDMA

As alluded to in earlier sections, SCPC has distinct advantages over conventional FDMA. Foremost among these is system flexibility. When combined with DAMA control, SCPC affords considerable system flexibility and expandability. Terminals can begin with a small pool of SCPC capabilities. As needs grow, capacity can be added on a channel-by-channel basis without affecting common equipment [Qua77, ScF84]. Unlike the fixed assignments of FDMA or TDMA, satellite utilization is independent from the number of terminals [Qua77].

2.7.3 Disadvantages

Similar to FDMA, SCPC suffers greatly from intermodulation noise. For high efficiency, DAMA equipment must account for the intermodulation products (IMP) and assign frequencies accordingly to sufficiently abate such effects. Algorithms with two different goals could be implemented: eliminating intermodulation noise or just reducing it to some acceptable level [OkY82]. In the former category are techniques such as Babcock's spacing [OkY82]. In IMP-free schemes, unfortunately, many potential assignments must be left unused and utilization suffers greatly. For example an IMP-free system requires about 14 times wider bandwidth for a group of 20 carriers and 20 times wider for a group of 30 carriers [OkY82]. At this expense, IMP-free techniques are simply not feasible.

Although a guaranteed minimal algorithm has yet to be found, various algorithms have been devised to reduce the effect of intermodulation products. These algorithms typically work in the following manner: insert a new carrier into a group, find the worst IMP in the group, move the carrier that causes the largest IMP, then repeat until some criterion is met [KoL95, OkY82]. For efficiency, only the third IMP is usually considered [KoL95, VuF85].

In terms of connectivity, terminals must support a variety of carriers to be reasonably connected. The central DAMA controller's scheduling problem becomes much more complex if terminals do not have sufficient frequency agility.

2.7.4 Applications

SCPC excels in the arena of thin route (less than about 12 channels per terminal) telephony [ScF84]. Other applications include handling overflow from other types of systems, mobile communications, and disaster recovery [ScF84]. SCPC's relatively low data rate makes it unsuitable for trunking applications or high data rate applications (for example video) [ScF84].

2.8 Centralized DAMA in Detail

Because the system under study uses a central control DAMA, this section supplements earlier material on DAMA system design. Specifically, this section further refines the traffic models and factors influencing efficiency (particularly the allocation algorithms).

2.8.1 Models of Traffic Supported

In general, models view incoming traffic as coming from several classes of users. Traffic from the same class demands the same resources (bit rate, bandwidth, power, etc.) [AeK77, Aei78, BaB82, WoG86]. Priorities among the classes can be set; for example, blocking probability, throughput, or delay [WoG86].

Overwhelmingly, researchers use Poisson arrival processes and exponentially distributed holding times to model circuit traffic [AeK77, Aei78, AiB90, MeG92, WoG86]. The requirement for exponential holding times is overly restrictive [BaB82, Kau81].

Packet data also is modeled as Poisson arrivals with fixed or exponentially distributed packet lengths [AiB90]. Unlike circuit traffic, data traffic's requirements (packet lengths) are known at the time of request and can aid in scheduling.

2.8.2 Performance

Performance considerations in a central DAMA system come from two sources: access to the controller via the contention channel and efficiency with which the allocation algorithm assigns channels. Since blocking leads to delay, and therefore influences throughput, blocking dominates considerations of efficiency.

Channel requests in a central DAMA system with a contention-based reservation channel block for three reasons: competition for the reservation channel, insufficient resources to establish a channel, or the destination terminal is busy [MeG92, PeM92, RaB80, Rap79]. Since the reservation channel is accessed by S-ALOHA, a hard upper limit on its utilization is 37%. Note that the load on the contention channel depends on the traffic load and not on the number of terminals. To remedy the long access delays associated with low utilization, more reservation channels could be allocated [Rap79]. The system under study supports up to eight request channels [DIS96]. If overall data channel utilization dominates performance considerations, terminals should buffer channel requests instead of operating in a blocked calls cleared mode [MeG92].

The second major source of blocking in DAMA systems is lack of satellite resources (bandwidth and power). Priorities established among user classes, and the means in which the allocation enforces these priorities, significantly effect performance for each class. In particular, blocking, delay, and throughput bounds can be established between user classes

[WoG86]. The allocation algorithm enforces the priorities between users subject to system constraints.

2.8.3 Resource Allocation

As was mentioned previously, the allocation algorithm strongly influences overall DAMA system performance. Continuing in the stepwise refinement mode, this section begins with a general overview of resource allocation strategies, then introduces mathematical representations of various strategies. These are examined for applicability to circuit and packet traffic.

2.8.3.1 Overview

The resource allocation strategy and the algorithm that implements it enforces a precedence policy among user classes subject to resource constraints. Constraints take the form of the policy decisions of the previous section and physical requirements. Primary physical constraints are bandwidth and power availability, the demand for which depends on the terminal figure of merit (G/T), data rate, modulation technique used, and forward error correcting coding [Fre74, PeM92]. Most analytic and simulation studies assume away these constraints, preferring to assume that the system operates bandwidth limited [AeK77, BaB82, WoG86]. A notable exception was conducted by Petr *et al.* where a database of "engineering data" took power and other factors into consideration [PeM92]. Further simplifying physical considerations, intermodulation noise and other nonlinearities are also usually assumed away [Aei78, AeK77, BaB82]. Rather than concentrate on the physical mechanisms underlying the channel requirements, most studies concentrate on

allocating a generic "resource," (*e.g.*, bandwidth), and assume that the channel requests have no delays accessing the controller. From this perspective, the problem of satellite capacity allocation can be viewed as a buffer management problem [WoG86].

The resource allocation strategy categorizes users into classes and controls their access to the resource. The system model differs slightly for circuit and packet traffic. For circuit traffic, the resource is the transmission capacity of the satellite. For packet traffic, the resource is the queue at the center (relay) terminal.

The strategies are classified by how they divide the overall resource among the user classes. At one extreme there is no division--all customers compete for the entire resource. This is known as a *complete sharing (CS)* strategy. At the other extreme, each user class receives a fixed portion of the resource. In this *complete partitioning (CP)* strategy, competition for the resource is limited to within each class. Between these extremes, somewhat less than the entire resource is divided among the classes. Arrivals whose class is saturated then compete for the remaining resource. This is known as *dedicated with shared overflow.* The dedicated portion may guarantee a user class a minimum allocation (*sharing with minimum allocation, SMA*), or restrict the allowed maximum allocation *(sharing with maximum capacity, SMXQ*). The boundaries between user class allocations may be static (*fixed boundary*) or adjustable (*moveable boundary*). Figure 2 graphically illustrates these strategies. Auxiliary algorithms can carry out preemption within or between user classes. For packet traffic this means that packets could be served in *first in first out (FIFO)*, or *last in first out (LIFO)* order.

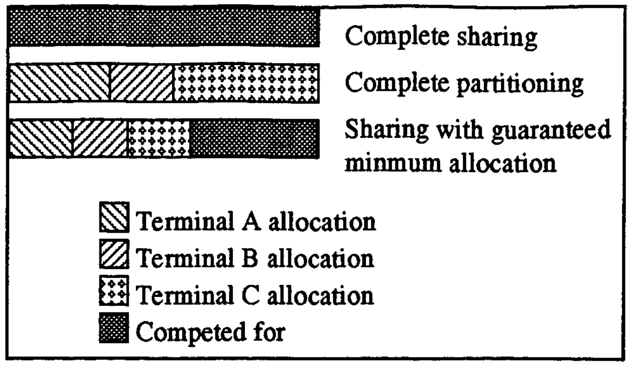

Figure 2. Resource Sharing Techniques Overview.

Analytical studies typically examine only complete sharing, complete partitioning and dedicated with shared overflow due to their analytic tractability [Aei78, AeK77, BaB82, Kau81, WoG86]. Preemption is rarely considered, and circuit systems always operate in a Erlang loss manner (blocked calls cleared) [Aei78, AeK77, BaB82, Kau81, MaJ75, WoG86].

Analytical and simulation results generally indicate that techniques based on sharing the resource among all arrivals result in better overall performance [Aei78, AeK77]. There are exceptions to this, however. For example, sharing with maximum capacity has been proven to optimize one of the selected performance criteria for three-class systems [WoG86].

2.8.3.2 Application to SHF-DAMA System

As detailed later, the allocation strategies applied to circuit traffic only indirectly establish precedence among user classes and do not directly support preemption. The SHF-DAMA system initially specifies five user levels and a system level of precedence. SCPC calls of higher precedence preempt lower precedence channels if resources need to be reclaimed [DIS96]. Thus, there is some question whether or not any of the allocation

strategies (other than complete sharing) apply directly to the SHF-DAMA system. It is believed that at minimum, implementing one of the strategies will provide insight into what the preemption probabilities are. Enforcing some order on the allocation may reduce the need for preemption. These are important results to be determined by this study.

Regarding packet data, the SHF-DAMA standard also specifies that priorities will be enforced. Because buffer space is ultimately limited in the network control terminal (relay terminals), some strategy must enforce the priority. No preemption is specified for packet services [DIS96].

2.8.3.3 Circuit Traffic Model

The following sections introduce notation and general system concepts. The notation is that of AeK77 and WoG86. Customers (calls) are classified as coming from K user classes. Each class i, i = 1...K is characterized by

- N_i the number of customers, may be infinite or finite
- λ_i the call arrival rate
- $1/\mu_i$ the average call duration
- c_i the capacity required per customer
- C_i the amount of resource guaranteed to the class
- M_i the maximum resource class i can consume
- W_i relative importance of class i
- B_i the blocking probability associated with class i
- T_i the throughput of class i (calls/time)

The satellite possesses C_0 units of capacity (bandwidth or power). This capacity can be divided linearly; *i.e.,* allocated to incoming calls without consideration of interference from other calls in progress. Recall that this effectively negates consideration of intermodulation noise. Fragmentation of the resource may occur in strategies that allow

the same portion of the resource to be shared among user classes with different per-call requirements. Algorithms implementing these sharing strategies must then account for which specific portions of the resource are allocated. All accepted calls are "processed" immediately and in parallel by the resource (channel) allocated to them. No preemption within or among classes is permitted.

2.8.3.4 Packet Traffic Model

The system and customer models closely parallel that of circuit traffic with some important nuances. For completeness, all of the relevant parameters are listed below. Customers (packets) are classified as coming from K user classes. Each class i, i = 1...K is characterized by

- N_i the number of customers, may be infinite or finite
- λ_i the packet arrival rate
- $1/\mu_i$ the average length of packets from class i
- c_i the capacity required per customer, the same as $1/\mu_i$
- C_i the amount of resource guaranteed to the class
- M_i the maximum resource class i can consume
- W_i relative importance of class i
- B_i the blocking probability associated with class i
- T_i the throughput of class i (packets/time)

The relay station possesses C_0 total units of capacity (buffer space). Packets may be initially rejected, accepted into the queue according to their priority and queueing discipline (FIFO versus LIFO), pushed out of the queue in deference to higher priority packets, moved in the queue according to subsequent arrivals, and served. All packets are processed by a common pool of servers and are thus served sequentially. Note that this

differs from circuit traffic where no calls are queued, and all accepted calls immediately begin service.

2.8.3.5 Allocation Strategy Model

The allocation strategies are characterized by how they divide the C_0 units of capacity among the K user classes. For convenience, define the vector $\mathbf{j} \equiv (j_1, j_2, ..., j_K)$ so that j_i represents the number of customers being served (circuits allocated or buffer positions occupied) from class i. With this notation, the resource constraint that all allocation strategies must enforce can be compactly represented as follows:

$$\sum_{i=1}^{K} c_i j_i \leq C_0 \tag{2.1}$$

The state of the system can be described by the vector **j**. An allocation strategy can be represented as the set of all possible vectors **j**, the allowable set or A-set [AeK77]. Geometrically, the strategy can be viewed as a K dimensional polyhedron in the first quadrant with a vertex at the origin. For example the complete partitioning strategy is represented by a K-dimensional box and the complete sharing strategy is represented as a tetrahedron formed by the positive axes and a tilted plane [AeK77]. The edges of the A-set determine the boundary at which calls are blocked. Thus blocking probability can be determined by summing along the edge of the A-set and other performance measures derived therefrom. Provided that the A-set (strategy) returns relinquished capacity immediately to the available pool of resources, the probability of being in any particular state **j** is given by:

$$P(\mathbf{j}) = P(\mathbf{0}) \prod_{i=1}^{K} V_i(j_i), \mathbf{j} \in \text{A-set} \tag{2.2}$$

where

$$V_i(j_i) = \frac{\left(\frac{\lambda_i}{\mu_i}\right)^{j_i}}{j_i\,!} \text{ if the population in group i is infinite, or} \tag{2.3a}$$

$$V_i(j_i) = \binom{N_i}{j_i}\left(\frac{\lambda_i}{\mu_i}\right)^{j_i} \text{ if the population in group i is finite, and} \tag{2.3b}$$

$P(\mathbf{0}) = P(0,0,...0)$, the probability that the system is empty [AeK77, WoG86]. So that all the probabilities sum to one, $P(\mathbf{0})$ is given by

$$P(\mathbf{0})^{-1} = \sum_{j \in A} \prod_{i=1}^{K} V_i(j_i). \tag{2.4}$$

Note two things from the above. First, the number of states $\mathbf{j}$ in an A-set can be very large. Thus direct computation of P(j) is not feasible. Second, note that the product term in the above equation does not depend on the A-set (strategy) but only on the traffic parameters. Only $P(\mathbf{0})$ depends on the A-set. Although it may not be feasible to calculate this analytically, it can be determined by observing the proportion of time the system is empty in a simulation of the strategy [AeK77]. Thus the blocking probability, B_i, can be determined by simulating the system, observing $P(\mathbf{0})$, and summing along the appropriate boundary of the A-set. The blocking probabilities, B_i, can be calculated in a much simpler fashion for the complete partitioning strategy in which the Erlang B formulas may be used. This is because the complete partitioning strategy eliminates all interaction between user classes.

2.8.3.6 Performance Criteria Model

Various criteria can be evaluated for an allocation strategy. Depending on the relative importance of users of each class, weights can be attached to the per-class performance measures to give an overall performance measure to be optimized. Optimizing blocking can be achieved by minimizing

$$\sum_{i=1}^{K} B_i W_i. \tag{2.5}$$

The throughput of class i is given by

$$T_i = \lambda_i (1 - B_i). \tag{2.6}$$

Thus the optimality criterion can be viewed in terms of maximizing throughput as maximizing

$$\sum_{i=1}^{K} W_i \lambda_i (1 - B_i) \tag{2.7}$$

which is the same as minimizing

$$\sum_{i=1}^{K} W_i \lambda_i B_i. \tag{2.8}$$

In terms of utilization of the individual classes, $\rho_i = \lambda_i/\mu_i$, the strategy would have to minimize

$$\sum_{i=1}^{K} W_i c_i \rho_i B_i \tag{2.9}$$

2.8.3.6.1 Complete Sharing

In this strategy, all user classes compete for all of the satellite resource. Circuits are established from all classes up to the point that Equation 2.1 would be violated. While this

certainly represents the simplest allocation strategy, it is not the most efficient and fails to ensure any fairness among user classes [Irl78, KaK80, ThA84].

2.8.3.6.2 Complete Partitioning

This strategy partitions the total capacity, C_0, in to K disjoint pools, $C_1..C_K$. Calls from class i are established up until the C_i pool is exhausted; i.e., calls are established so long as its acceptance would not violate the following constraint:

$$c_i j_i \leq C_i \tag{2.10}$$

Note that in completely partitioning the resource, all competition between classes is eliminated. Thus performance measures for each class can be calculated from the classic queueing models, particularly the Erlang B or Erlang C equations. To account for changing traffic patterns, the partitions have to be periodically updated [AeK76]. A number of heuristics have been developed to determine when and how to update the partitions so that the specified performance measures are met [Irl78, TiS88].

2.8.3.6.3 Sharing with Minimum Allocation and Sharing with Maximum Allocation

To partially alleviate the potential for unfairness between user classes seen in complete sharing, a minimum quantity of resource can be allocated to each user class. Any additional resource needed is competed for among all user classes from a common pool. Mathematically, for all user classes i

$$C_i \geq 0 \tag{2.11}$$

$$\sum_{i=1}^{K} C_i < C_0 \,. \tag{2.12}$$

Similarly the maximum allocation to a given class can be restricted. Mathematically, for all user classes i,

$$C_i \geq 0 \tag{2.13}$$

$$M_i \geq C_i \tag{2.14}$$

$$\sum_{i=1}^{K} C_i < C_0 \tag{2.15}$$

$$\sum_{i=1}^{K} (C_i + M_i) \geq C_0 \,. \tag{2.16}$$

This of course effects performance. If a class is underutilized and others overutilized, reserving capacity for each class lowers throughput. Similarly, restricting the maximum allocation raises the blocking probability.

2.8.3.7 Priority Determination

Note that in the above strategies, no explicit priority is given to a particular user class. Rather, priorities are determined by allocating resources such that the projected blocking probabilities do not exceed some threshold. Other than reallocating the total resource C_0 among the K user classes, no preemption takes place. The inclusion of interclass preemption on a call-by-call basis leads to intractable analytic models [AeK76, AeK77].

2.8.3.8 Relationship Between Strategies and Algorithms

Discussions so far have concentrated on "allocation strategies" and not on "allocation algorithms." It can be readily seen that algorithms implement the strategies in

a straightforward manner. In the case of complete sharing the following would be executed upon a call request:

```
Procedure Complete_sharing_accept_or_not
  Let CNOW be the capacity currently allocated
  IF CNOW + ci < C0 THEN
     accept the call
     CNOW = CNOW+ ci
  ELSE reject the call
```

Similarly for complete partitioning, two algorithms are needed:

```
Procedure Complete_partitioning_accept_or_not
  Let CNOW be the capacity currently allocated to the incoming class
  IF CNOW + ci < Ci THEN
     accept the call
     Ci = CNOW+ ci
  ELSE reject the call
```

For the resource allocations:

```
Procedure Complete_partitioning_reallocate_resources
   IF traffic has changed significantly since the last allocation
  THEN
     Compute resources needed by each class to optimally meet the
  specified performance criteria.  (Note that this step has been the
  subject of much research)
        Adjust the resource allocations as possible when calls
  terminate.
```

2.9 The SHF Demand-Assigned Multiple Access Standard

To address problems of a crowded spectrum and enable autonomous control, the Military Communications Electronics Board drafted the SHF Demand-Assigned Multiple Access (DAMA) Standard. The standard specifies the waveform, communications and control protocols, and management functions for packet and circuit traffic over the C, X, and Ku bands. The standard strives to maximize utilization of space segment resources and automation of resource assignment [DIS96, DoP94]. In light of previous discussions, the SHF-DAMA system can be classified as a central control DAMA system supporting

data via time-shared FDMA links, and SCPC voice and data using a variable number of contention-based reservation channels.

2.9.1 SHF-DAMA System Control Architecture

The SHF-DAMA Standard envisions intercommunicating regional satellite networks supporting global communications. Within each network, a hierarchy of control dynamically partitions space segment resources. At the top of the network control hierarchy, Satellite Network Control Centers (SNCCs) partition bandwidth to multiple network control terminals (NCTs). NCTs in turn manage resources for one to 512 subordinate network terminals (NTs). The NTs provide ultimate connection of user equipment to the satellite network. NCTs themselves may play the role of a NT in a higher level subnet. Only exhaustion of the address space restricts the number of layers nested in this manner.

2.9.2 DAMA Services and Enabling Mechanisms

2.9.2.1 Data Service

Data services utilize a packet protocol, supporting both fixed length (3120 bytes) and indefinite length (e.g., file transfer) messages. The NCTs serve as hubs for all message traffic and enable point-to-point and point-to-multipoint services.

2.9.2.2 Circuit Service

The standard specifies two types of circuit services: hub- (i.e., NCT-) assisted and direct (i.e., NT-to-NT). Either type may require full or half duplex services. In the case

of full duplex, asymmetric data rates are supported. Single-channel-per-carrier (SCPC) circuits assigned on a demand basis support all circuit traffic.

2.9.2.3 Control--The Common Signaling Channel

A Common Signaling Channel (CSC) provides control of the above services. The NT-to-NCT communications operate on one to possibly eight TDMA carriers (the Inbound CSC). Time-shared, NCT-assigned FDMA links from the NTs to the NCT support message traffic. NCT-to-NT communications, including packet data and control information, take part on a TDM carrier (the Outbound CSC) also known as the Forward Channel.

2.9.2.4 Bandwidth Utilization and Resource Allocation

The SHF-DAMA Standard specifies in detail the procedures for accessing the Inbound CSC to request bandwidth. The standard leaves unspecified methods for resource allocation by the NCTs and the Satellite Network Control Center (SNCC). The NCTs must also estimate their requirements before requesting resources from the SNCC. In turn, the SNCC must balance resource requests from its various NCTs. Again, the standard leaves unspecified how this will be done [DIS96].

2.10 Link Analysis

To understand the various resource limits inherent in a satellite communication system, a understanding of link analysis is necessary. This section covers that arena.

Electromagnetic signals undergo various changes during their propagation from transmitter to receiver. The goal of link analysis and its result, the link budget, is to take

account of these changes such that the signal received at the receiver (in the case of the SHF-DAMA system, the destination network terminal) is of sufficient quality to support the desired channel.

A brief list of major factors effecting link quality includes the following [Mar86, Skl88]:

- transmitter power (Effective Isotropic Radiated Power, EIRP)
- free space loss, due to the spreading of the signal over a distance
- receiver antenna gain, G_A
- receiver noise figure (G/T)
- bit rate

In a non-regenerative transponder, such as the Defense Satellite Communications System (DSCS) III transponder #2 to be used for the SHF-DAMA service [DIS93], the total satellite power is divided among all inbound signals, thus introducing the number of accesses as another factor effecting link quality [Skl88].

Values for the above quantities are frequently measured in Decibels, as related in the following equation:

$$XdB = 10 \log_{10} X \tag{2.17}$$

Relating the values in this manner enables the satellite link engineer to add the various gains and subtract the various losses, rather than multiply and divide by large (or small) quantities. For example a free space loss of $2.75422 * 10^{-20}$ can be represented as -195.6dB.

EIRP relates the power of the transmitter to the power of an isotropic (uniform in all directions) transmitter in the direction of greatest gain of the transmitting antenna. For example, a transmitter with a power of 30 dBW (Decibel Watts) and a transmit antenna gain of 15 dB has an EIRP of 45 dBW (in the direction of greatest gain), the same as an isotropic transmitter of 45 dBW. In terms of mathematics,

$$EIRP = P_T G_T \tag{2.18a}$$

where:

P_T is the power of the transmitter in Watts, and

G_T is the gain of the antenna.

In terms of Decibels,

$$EIRP\ (dBW) = P_T(dBW) + G_T\ (dB) \tag{2.18b}$$

Free space path loss results from the spreading of the signal over distance. At geosynchronous altitudes (approximately 22,000 miles) path loss accounts for the single most significant loss to a signal [Skl88]. Path loss depends on frequency, with representative figures for the SHF-DAMA system being 202.2 dB loss on the uplink and 201.4 dB on the downlink [SKL88, DIS93].

The receiver noise figure relates how much noise the receiver introduces into an incoming signal. All conductive material at higher than 0 Kelvin (0K) possesses randomly moving electrons that serve ultimately to introduce unwanted energy to an incoming signal. Because the noise is added throughout the frequency spectrum of the receiver, it is convenient to think of the receiver as possessing a density of noise, the noise power density. The total noise of the receiver, can then be related by following equations:

$$N_0 = kT \tag{2.19}$$

where

N_0 is the noise power spectral density in W/Hz.

k is the Boltzmann's constant, $1.38 * 10^{-23}$ W/K-Hz, or -228.6 dBW/K-Hz.

T is the receiver temperature, Kelvin.

$$N = kTW \tag{2.20}$$

where

N is the noise power (Watts).

W is the system bandwidth (Hz).

This noise power is then introduced into the transponder (amplifier), along with the incoming signals. The receiving terminal also introduces noise similarly. Two things result from this unwanted noise: the transponder power is consumed by noise, thus lowering the effective gain of the transponder; and, the terminal receiver further compounds the problem. Noise of a receiver often is expressed as its noise figure (G/T), where G is the gain of the receiving antenna and T is the noise temperature of the receiving system.

Not all signal impairments are constant. Many, such as atmospheric attenuation, can vary considerably, as much as 14 dB [Skl88]. For this reason, link budgets always contain some measure of margin--a reserve of power transmitted to assure link quality.

With regard to the quality of the received signal, in the case of digital transmissions this is measured as the probability of a bit in error. Generally, terminal equipment may be able to correct up to a certain level of errors, or perhaps the end service itself can tolerate

a certain bit error probability. The primary determining factor in the determination of the bit error probability is the ratio of the energy each bit contains to the noise power, denoted E_b/N_0. Various digital coding schemes require different E_b/N_0 for the same probability of error [Mar86]. Given a coding scheme, though, E_b/N_0 depends on the energy transmitted, the bit rate, and the total noise.

To review, the goal of link analysis is to account for various factors such that a minimum E_b/N_0 is achievable over each channel. A simplification to further calculations occurs in the absence of intermodulation products, when

$$(E_b/N_0)_{ov} \cong (E_b/N_0)_u + (E_b/N_0)_d \tag{2.21}$$

where

$(E_b/N_0)_{ov}$ is the overall (uplink and downlink) E_b/N_0.

$(E_b/N_0)_u$ is the uplink E_b/N_0.

$(E_b/N_0)_d$ is the downlink E_b/N_0 [SKL88].

Using the above, the power received by station j from station r is given by

$$P_{rj} = EIRP_s \, \gamma_j \left(\frac{A_i P_i}{P_t + N_s W} \quad \frac{P_t - A_i P_i}{P_t + N_s W} \quad \frac{N_s W}{P_t + N_s W} \right) + N_g W \tag{2.22}$$

where

P_{rj} is the power received by the jth terminal from the rth terminal.

$EIRP_s$ is the satellite EIRP.

γ_j accounts for the downlink losses and receiving antenna gain of the jth terminal.

A_i is the r's proportion of total uplink power received + the satellite noise.

P_i is r's proportion of the total uplink power.

P_t is the total uplink power.

N_s is the noise of the satellite.

W is the bandwidth of the system.

N_g is the noise of the receiving ground terminal [Skl88].

Using a scenario from the 1993 SHF-DAMA Draft Standard, Appendix B outlines a link analysis and budget [DIS93]. Note that a total of 400 simplex (one way) channels may be supported at 9600 bits per second, using the specified network terminals and transponder power.

2.11 Traffic Analysis

Communications systems have long proven amenable to queueing theory analysis. Call setup delays, queueing probabilities, blocking probabilities, and a host of other performance parameters can be calculated with a few simplifying assumptions. For a communications system with m servers (potential channels), operating in a blocked calls queued mode, the following apply:

$$p_0 = \left[\sum_{k=0}^{m-1} \frac{(m\rho)^k}{k!} + \frac{(m\rho)^m}{m!} \frac{1}{1-\rho} \right]^{-1} \qquad (2.23)$$

where

p_0 is the probability of the system being empty.

ρ is the server utilization factor.

$$P[\text{queueing}] = p_0(m\rho)m \,/\, [m!(1-\rho)] \text{ (Erlang C)} \qquad (2.24)$$

These formulas are used to validate the simulation results.

2.12 Chapter Summary

In a stepwise refinement process, this chapter introduces the subject of multiple access communications. It presents background with the goal of understanding issues relevant to the system under study. In particular, root communications concepts and multiple access techniques are refined and contrasted. Special attention was then placed on single-channel-per-carrier modulation and the centralized demand-assigned multiple access (DAMA) protocol. The SHF Demand Assigned Multiple Access (SHF-DAMA) standard is presented in light of prior discussions. Finally, mathematical treatment is given for numerous aspects of satellite link engineering and traffic engineering.

3. Methodology

3.1 Introduction

While the previous chapter outlined background necessary for understanding the system under study, this chapter focuses on the study itself. Accordingly, the discussion includes the following:

- restatement of the problem
- scope of this effort
- operating assumptions
- approach
- expected results
- satisfaction criteria

3.2 Problem Statement, Investigation Goals

In light of the background presented in the preceding chapter, the problem can be succinctly reformulated:

This effort characterizes the performance of the SHF-DAMA architecture using various resource allocation algorithms implemented by the network control terminals (NCTs). These algorithms implement the complete sharing, complete partitioning, and mixed type policies and include preemption. System measures of performance include the following:

- SCPC traffic: queueing probability, preemption probability, connection establishment delay

- message traffic: end-to-end delay
- general: resource utilization to include forward channel usage, Return Orderwire (ROW) usage, inbound data communication channel (I-COMM) usage and satellite utilization.

3.3 Scope

This section briefly outlines the bounds of this effort. A rationale is also provided for those bounds.

3.3.1 Network Topology and Traffic

A single NCT and its network of NTs is considered. The number of NTs is varied to produce no queueing, moderate queueing , and an overloaded system.

Communications between satellite subnetworks is not examined. This is because all NCTs implement the same algorithms. Also, traffic to and from another subnetwork could be viewed as coming from an additional terminal or terminals. Thus, only a single subnetwork needs to be considered. Similarly, only one level in the DAMA network hierarchy needs to be considered. Subordinate networks manage their portion of satellite resources using the same algorithms. Also, when traffic remains within a network, the parent NCT has no interaction with the subordinate network other than initially releasing a portion of resource (Figures 3 and 4).

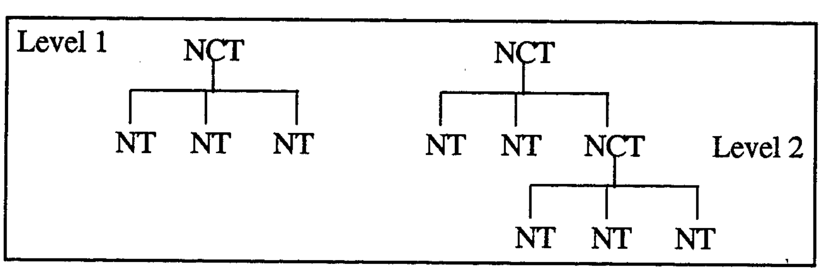

Figure 3. One and Two Level DAMA Networks.

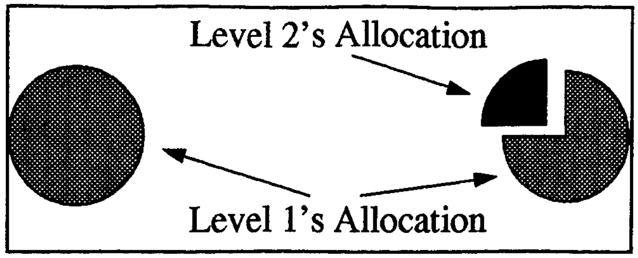

Figure 4. One and Two Level Resource Availability.

3.3.2 Physical Mechanisms

Considerations of physical mechanisms underlying the actual microwave transmission are minimal. Effects such as rain attenuation, scintillation, multipath fading, and other sources of errors are ignored. Spurious errors affect only message-based transmissions, those of the Forward Orderwire (FOW), Return Orderwire (ROW), inbound data communications channel (I-COMM), and outbound data communications channel (O-COMM). Spurious errors, therefore, do not affect the allocation of satellite resources to SCPC circuits. Of course, to maintain a specified bit error probability, the SCPC circuit will have to be allocated sufficient power resources. Similar to previous studies [Aek76, Bab82, NgS90, Rap79, WoG86], this study focuses on the allocation of the system's overall resources and not on the detailed protocols for error-free end-to-end transmission. The primary physical considerations are that the satellite transponder (a DSCS III transponder) possesses a finite capacity and that the power required for a given bandwidth is constant.

3.4 Operating Assumptions

This section briefly outlines items assumed for this effort. Consequences of these assumptions are also outlined.

3.4.1 Allocation Algorithm Selection Criterion

System performance drives the resource allocation algorithm selection. Cost of implementing the algorithm in terms of NCT complexity is unimportant. The original problem statement furnished by this effort's sponsor requested that algorithms be investigated so that the terminals could be sized to implement them, indicating that system cost and complexity were not factors.

3.4.2 Division of Satellite Capacity

The satellite's bandwidth and power resources is divided linearly. That is, allocating a portion to one channel has no effect on another channel (other than the reduction of available overall resource). Recall that this negates consideration of intermodulation noise. As outlined in the previous chapter, algorithms exist to minimize the effect of intermodulation noise in single-channel-per-carrier (SCPC) systems. Those, however are not the thrust of this investigation and provide an area of opportunity for further research. Incorporating those algorithms into the present study simply involves modifying the allocation algorithm to identify portions of resource not optimal for allocation.

3.4.3 Terminal Uniformity

All terminals have the same figure of merit (G/T). Thus, no matter which terminal requests X amount of bandwidth, Y amount of power is allocated as well. The 1993 draft of the SHF-DAMA standard projects that any mix of six different terminal types may participate in the network [DIS93]. This study focuses on a single terminal type and includes provisions for varying the terminal type on a per-terminal basis. Allowing a mix

of terminals introduces an additional parameter to vary. This would lead to a combinatorial explosion of scenarios to investigate and is not feasible given the time constraint of this project. Restricting consideration to a single terminal type also effectively eliminates any prospect of a capture effect for the terminals' S-ALOHA access to the FOW.

3.4.4 Minimal Terminal Configuration

Though the terminals' transmission characteristics are assumed similar, the terminal configurations may vary. In particular, the number and types of modems supported by different terminals may vary. At a minimum, though, each terminal supports transmission and reception of control information concurrently with at least one data/voice channel. The SHF-DAMA standard makes provisions for terminals which support only one channel at a time, thus either processing control messages or handing data exclusively. Given the capabilities of the terminals specified for operation over these networks, it is unlikely that a terminal would possess only one modem. Accordingly, emphasis is not placed on this potentiality.

3.5 Approach

This section briefly outlines the overall processes needed to achieve the investigation goals. Means for achieving the processes are also outlined.

3.5.1 Phase 1: Infrastructure Development

During this first phase, the salient features of the SHF-DAMA system are extracted and modeled. These include the control and data channels (forward channel--FOW and

O-COMM, ROW, I-COMM, SCPC), traffic generators (SCPC voice, SCPC data, message), controllers (FOW and ROW message processors), receivers and transmitters for the FOW and ROW, and allocation schemes. Although not the direct goal of this investigation, development of the infrastructure needed to model the SHF-DAMA systems and protocols constitutes a major undertaking and can itself be considered a product of this investigation. Included below are brief descriptions of each of the major components.

3.5.1.1 Messages

Messages form the foundation of all control in the SHF-DAMA system. Accordingly, FOW messages, ROW messages, and packet data are modeled as data structures matching those in the SHF-DAMA message format draft standard, MIL-STD-188-167. While not all fields are modeled (for example the TRANSEC parameters), all of the fields used for allocation and scheduling are modeled. Each simulated message also contains additional information such as length in bits and data rate to facilitate easier calculations within the system.

3.5.1.2 Forward Channel

Recall from the previous chapter that the forward channel (FC) includes both the Forward Orderwire (FOW) and outbound communications channel (O-COMM). The FOW conveys control messages and the O-COMM includes packet data. The number of messages may vary frame-to-frame and each O-COMM transmission may be at a different bit rate. At any given time, there are two FOW frames in existence--the one just transmitted and being processed by the NTs, and the one being prepared by the NCT for

transmission. If frame durations are shorter than the round trip propagation delay of 250 ms, then more frames exist--NT received, NCT prepared, and "in transit."

Due to the dynamic nature of the forward channel, it is modeled by a (pair of) simple list(s) of messages. The NCT controller packs each frame with control and data traffic subject to the frame length restriction. After the transmission of that frame, NTs glean FOW messages and data addressed to themselves.

3.5.1.3 Return Orderwire

The Return Orderwire consist of from one to eight channels. Each channel contains a fixed number of blocks, dynamically divided by the NCT between a reserved section and contention section. Similar to the FC, this is modeled by lists of messages. Each ROW reserved section is implemented as a list in which the specified NTs "transmit" their control messages. The contention portion is also simply a list messages, but with the addition of a slot number field. After all contention messages are loaded, the ROW searches for common slot numbers (a collision) and removes all messages with common slot numbers. Messages that have not collided are simply added to the list. Note that the messages might be added "out of order"--an NT may transmit in slot 45 before another actually places something in slot 10 for example. All that matters, though, is that collided transmissions are removed and others are passed on to the NCT.

As with the FC, two versions of the ROW need to be maintained. One supports the ROW frame(s) currently being filled by the NTs and the other supports the NCT readout of the previous frame(s). Again, if frame rates increased such that the frame time was less

than the round trip propagation delay, additional copies would need to be implemented to account for the frames "in transit."

3.5.1.4 Inbound Communications

The inbound communications channel (I-COMM) consist of from one to eight channels with NT accesses scheduled by the NCT. Appropriately then, the I-COMM is modeled simply as a list of messages "transmitted" by the NTs. Previous allocation of I-COMM space is received over the FOW. Similar to the ROW, data may be added in any order without loss of realism.

3.5.1.5 SCPC

The transfer of data or voice over SCPC circuits is not modeled. Any end-to-end protocol needed for transmission of data or voice is assumed to exist and is outside the bounds of this study. This study models the establishment of SCPC circuits, subject to system resource availability. Accordingly, the related control messages are handled in the FOW and ROW as already delineated. The circuit itself is modeled as occupying a quantity of bandwidth and power from the time the NCT assigns the circuit until the time the NCT receives the circuit teardown request. Thus, it is simply a user of a non-consumable resource.

3.5.1.6 Network Terminal

Network terminals use the aforementioned channels to request and use services. Accordingly, they are composed of the following components:

- SCPC voice call generator
- SCPC data call generator

- Data packet generator
- Service request message queue
- FOW/O-COMM receiver
- Incoming FOW message processor
- ROW message transmitter
- I-COMM transmitter
- Modem bank manager
- Call timer

Similar to the proposed scenarios of [DIS93], the generators produce requests for channels according to a Poisson process with mean interarrival time of 30 seconds and mean duration of 3 minutes. These requests are then queued, awaiting a successful transmission on a contention slot of the ROW. The NCT uses the parameters of the request to allocate bandwidth and power returning the assignments over the FOW. A timer awaits the end of the SCPC circuit. The modem bank manager can determine what modems are engaged and reports this information to the NCT in order to determine whether a connection is possible or not.

3.5.1.7 Network Control Terminal

The network control terminal is very similar to a NT. Besides the service request generation and message processing functions, the NCT also contains resource allocation components. The NCT components are summarized in the following list:

- SCPC voice call generator
- SCPC data call generator
- Data packet generator
- Service request message queue

- ROW message receiver
- FOW message generator/ROW message processor
- I-COMM slot allocator
- Satellite resource allocator
- Modem bank manager

Many of these components are common to the NT. The FOW message generator/ROW message processor implements the protocols for service establishment, maintenance, and teardown. It uses the allocators to access and manage the control and data channels.

3.5.2 Phase 2: Allocation Algorithm Development

After all supporting architecture is in place, the resource allocation algorithms are developed and tested. These algorithms are executed by the NCT and manage the SCPC channels. Again, algorithms developed include complete sharing, complete partitioning, and sharing with minimum allocation. These algorithms are compared both including and excluding preemption.

3.5.3 Phase 3: Traffic Mix Definition

The 1993 SHF-DAMA draft outlines three traffic mix scenarios for a single class of users [DIS93]. A distribution of the proportion of users in each class needs to be determined, leading to the following:

- voice call demand: generation rate and duration distributions per class
- circuit data calls: generation rate and duration distributions per data rate per class
- packet data: generation rate and quantity distributions per class

The 1993 standard assumes an unrealistic uniform destination scheme. The 1993 standard also specifies that a DSCS III transponder is used and gives expected microwave link parameters. These bound the overall resource to be allocated.

3.5.4 Phase 4: Verification and Validation

Individual components are verified as they are built and integration testing done in a bottom-up manner. Validation of system fidelity is done by comparing protocols specified in the 1996 SHF-DAMA draft standard with implemented routines. Outputs for the analytically tractable allocation schemes (non-preemptive complete partitioning) are validated against results from the Erlang C formula.

3.5.5 Phase 5: Production Runs, Data Reduction, and Reporting

Data reduction and summarization proceeds concurrently with the production runs. As specified in the satisfaction criteria, runs are replicated until a valid statistical comparison can be made between allocation algorithm performance. Naturally, final reporting occurs after the last of the data summary and is found later in this report.

3.5.6 Simulation Tool

The MODSIM II for the Sun-4/Sparc Station environment implements the simulated system. As a custom coding environment based on C++, it allows a high degree of flexibility based on a standard language. The complexity of interaction among NTs and NCT dictate a highly flexible modeling tool. Implementation of the allocation algorithms involves engineering and other computations not easily done with currently available graphical based tools. On an administrative level, ample access to the MODSIM II

environment is available throughout the course of this investigation. Also, because the designer can determine the exact statistics to be collected, runtime overhead is minimized.

As stated before, MODSIM II is based on a standard language, facilitating communication to future users and maintainers. MODSIM II support for the simulation itself includes scheduling and tasking routines, random number generators, and a library of objects to build upon. Some statistics such as resource mean usage and standard deviation are automatically calculated.

3.5.7 Alternate Approaches

Alternate overall approaches include a completely analytic analysis or completely simulation-based evaluation. Given the complexity of analytic models for all but the simplest allocation schemes, a fully analytic analysis is not possible. Similarly, a simulation with no analytical results to verify against cannot be fully relied upon.

Other simulation environments could be used instead of MODSIM II. While being more flexible, a complete C++ implementation would require too much verification. Root functions such as task scheduling, time management, etc. would have to be implemented as well as all statistics collection routines. At the other end of the spectrum, a graphical based environment such as BONeS® DESIGNER™ could be used. While this would facilitate quick implementation of message flow, implementing the protocols and allocation algorithms would still have to be done in custom code. Incorporating custom code into a graphical tool introduces an unnecessary level of complexity and would be a barrier to exportation of the model.

3.6 Expected Results, Hypotheses

Based on available literature, some version of a mixed allocation scheme will prove best suited when preemption is disabled. By reserving some bandwidth, all classes of users are guaranteed some access, and therefore some upper bound on the queueing probability and circuit establishment delay. Satellite utilization cannot be maximized if resources are fully partitioned and each class does not maximize use of its partition. Thus some degree of free competition for resources or some reallocation of resources is necessary to maximize utilization. The investigator hypothesizes that schemes based on sharing will outperform those based on rigid constraints. How the sharing-based algorithms will compare, in particular whether complete partitioning with moveable boundaries or sharing with minimum allocation more efficiently allocates resources, is unknown.

When preemption is enabled, the queueing probabilities for all but the lowest class of customer are essentially zero. Whether implementing an allocation strategy intended for use in a non-preemption environment will allow better resource management in a preemptive environment is a fundamental question of this study. The investigator hypothesizes that with preemption enabled, no allocation algorithm will conclusively outperform any other. The only difference will be the complexity of the implemented algorithm.

3.7 Satisfaction Criteria

This study will conclude when the following have occurred:

- System modeled as above

- Simulation model validated against analytical results for tractable non-preemptive schemes
- Performance parameters calculated for each allocation algorithm such that valid statistical conclusions can be drawn as to which allocation scheme performs best
- Data reduced and conclusions drawn about network performance under each of the algorithms under study
- Results documented

3.8 Chapter Summary

Building on the previous chapter's background, this chapter focuses on the study itself. Following a restatement of the problem, the limitations and assumptions of the effort are explored. The approach to the investigation was then stepped through, including the model description and processes to be followed. Alternatives were then examined, expected results proposed and satisfaction criteria delineated.

4. *Analysis and Results*

4.1 Introduction

This chapter begins by reviewing the purpose of this study. Next, Sections 4.2 and 4.3 examine elements of the simulation and experiment design. Section 4.2.9 discusses validation. Section 4.4.1 relates graphical analysis of the standard and per-message backoff results while. Section 4.4.2 examines statistical analysis of the simulation results. Finally, Section 4.4.2.4 then presents the final conclusions.

4.1.1 Research Questions

Recall from the previous chapter that this investigation seeks to characterize the performance of the proposed SHF-DAMA system using various resource allocation algorithms. Primary measures of performance are SCPC channel establishment delay and preemption probability for each class of customers; and resource utilization in terms of both power and bandwidth.

4.1.2 General Methodology

Simulations imitate the behavior of SHF-DAMA network terminals (NTs), the network control terminal (NCT), and the Forward and Return Orderwires. This behavior includes service request generation; transmission to the NCT; resource allocation and attendant request queueing by the NCT; and, notification to the NTs of

successful/unsuccessful call setup. Only SCPC data traffic is considered, due to the duration of this study.

Standard code representing the NTs, channels, and most of the NCT is used across investigations of the different allocation algorithms. To consider different allocation algorithms, code implementing the particular algorithm is incorporated with otherwise unchanged NCT code. Results from these different versions executing a common scenario are then compared.

4.2 System Design

The following subsections expand the system design outlined in Sections 2.8.3 and 3.5.1.

4.2.1 General Comments

The simulation developed consists of about 6800 source lines (including comments) of MODSIM II code. Sun SPARC 20's execute the simulations. A standard spreadsheet program assists in the analysis of simulation output.

Figure 5 on the next page depicts the entities and data modeled for SCPC service management:

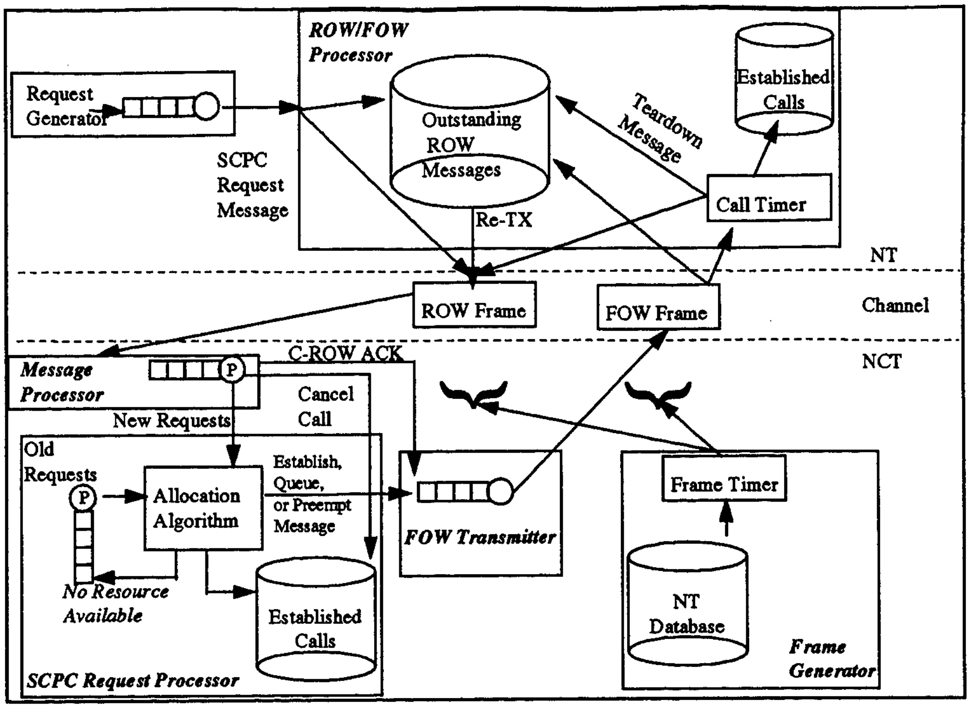

Figure 5. System Architecture Overview.

4.2.2 NT/NCT Architecture

The NTs consist of the following major components:

- Service request generator
- Request queue
- Return Orderwire (ROW) manager (transmitter/retransmitter)
- Established call database
- Call timer
- Forward Orderwire (FOW) message processor

The NCTs consist of the following major components:

- ROW message processor
- NT database
- Resource allocator
- FOW message generator
- FOW transmitter
- Frame duration controller

4.2.3 Service Requests

Service requests contain the following main information as well as administrative data:

- Source and destination NTs
- Priority
- Bandwidth required in the forward and return directions
- Power required in the forward and return directions

4.2.4 Channels

The channels consist of multiple lists of messages (frames). At times when the NCT begins a new frame, the NCT and the NT increment which frame they read from and write to. Messages that would not arrive at their destination within the current frame's duration are delayed until the next frame, but maintain their original frame's ID. Thus the NTs receive some data out of synchronization from the NCT's frame and vice versa. This models the propagation delay.

4.2.5 Allocation Algorithms

This study investigates three allocation algorithms: complete sharing (CS), complete partitioning (CP), and sharing with minimum allocation (SMA). These constitute not three distinct algorithms, but rather the same algorithm with differing proportions of the resource being shared among user classes: CP shares none, CS shares all, and SMA shares some middle proportion. Nevertheless, three separate pieces of code implement the three algorithms. This results in a greater degree of face validation between the algorithms--by

comparing SMA with no shared resource against CP, and similarly for SMA with all the resource shared compared to CS.

4.2.5.1 *Algorithm Descriptions*

This subsection elaborates the pseudocode descriptions of the main allocation and allocation-related algorithms given in Section 2.8.3.8.

4.2.5.1.1 *Boundary Setup: CP, CS, and SMA*

From one perspective, CP, CS, and SMA differ only in the amount of resource open for free competition among user classes. Of course, CP and SMA may establish the boundaries among user classes in various proportions, though the same quantity of resource is open for free competition. Because of the similarities, a common routine establishes the boundaries.

The satellite system designer first inputs how much of the resource is open for free competition. For CS, this is 100%; for CP, 0%; and, any value between 0% and 100% for SMA. Then, the designer inputs how the remaining reserved resource is to be divided among user classes. As an example, say the following parameters apply:

- Total resource: 400 units
- Portion to be freely shared: 20%
- Proportion of reserved resource for class ROUTINE: 25%
- Proportion of reserved resource for class PRIORITY: 50%
- Proportion of reserved resource for class FLASH: 20%
- Proportion of reserved resource for class FLASHOVERRIDE: 5%

In this case, 80 units would be freely competed for, 400*0.8*0.25 = 80 would be reserved for the ROUTINE class, 160 for the PRIORITY class, 64 for the FLASH class, and 16 for the FLASHOVERRIDE class.

4.2.5.1.2 Resource Allocation for a Call

Also, due to the similarity of the algorithms the allocation routines are similar. When a call request arrives, the amount of resource currently allocated to that call's class is compared to the maximum that the class is guaranteed. If there is sufficient remaining unused resource (either guaranteed to that class or open for competition), the call is immediately established and a message to that effect is sent to the requesting NT. If sufficient resource is not available, the algorithm then examines all lower priority classes (if any) to see if any has not used all of its guaranteed resource. If any unused resource is found, the algorithm "steals" resource from the lower level class, makes note of this so that the resource can be returned to the proper class, and establishes the call. If sufficient resource cannot be gleaned from lower level classes, a call from the lowest level is preempted with both establishment and preemption messages going to the appropriate NTs.

For each call, the amount of resource it takes from its class' guaranteed amount, and from the shared pool, is computed. In this way, resources can be returned to their proper place upon call teardown. Note that for CP the calls use no shared resource, and for CS the calls use only shared resource.

Although the allocation algorithms are in principle the same, minor differences exist for CP and CS. Because CP shares no resource, execution efficiency is increased by

deleting those instructions that check the availability of shared resources. Similarly, code checking the call's class' allocation boundaries is superfluous for CS, as all of the resource is shared and there are no boundaries.

4.2.5.1.3 Establish Call

The same algorithm establishes calls for all allocation algorithms. After the algorithm determines a call connection is possible, the current allocation for the class is incremented by the call's in-class and shared resource amounts. Similarly, the amount of shared resource is decremented by the call's shared resource amount.

4.2.5.1.4 Teardown Call

Call teardown undoes the bookkeeping of call setup and of resource allocation. Specifically, it returns the call's shared resources to the shared pool and decrements the class' current allocation by the call's shared and in-class resources. If this call required a boundary realignment by "stealing" resource from another class, the resource is returned to that class.

4.2.5.1.5 Reallocation Before Preemption

A unique feature of the algorithms is their ability to reallocate unused resource from one class of customer to another to avoid preempting any calls. For example, suppose the PRIORITY category has exhausted all of its minimum guaranteed resource and there is insufficient shared resource to establish a new PRIORITY call. If the ROUTINE category has not exhausted its minimum guaranteed allocation, the algorithm "steals" resource temporarily for the next PRIORITY call. Following the call, the algorithm replenishes the

"stolen" power and bandwidth, thereby moving the boundary towards its original location. The temporarily reduced level of resource available to the lower category raises its probability of queueing, but the investigator views this as a minor tradeoff for the benefit of the lower class' established calls not being unnecessarily preempted. This realignment feature is only enabled when preemption is also enabled to allow comparison of the algorithms as published in the literature versus preemptive, realignment-activated versions.

Literature reviewed for this study does not address this type of realignment algorithm. Rather, either the algorithm does no realignment or preemption, or it does preemption only. The special case of complete partitioning with moveable boundaries differs from the algorithm implemented in that boundaries are realigned periodically based on some gross loading factor (as described in Section 2.8.3.8), and not on a call-by-call basis. Thus classical CP with moveable boundaries does not immediately give back the resource at the completion of call.

4.2.5.1.6 Preempt Calls

To preempt a call, the allocation algorithm determines the minimum resource required to be liberated. This parameter is then used to select call(s) from lowest priority on up for preemption. Each selected call is torn down with a message generated to the effected NTs.

4.2.6 Backoff Algorithms

To handle retransmission of collided requests on the Return Orderwire, the SHF-DAMA standard defines a ROW backoff number transmitted in each Forward Orderwire

frame [DIS96]. Each FOW frame contains the number of a ROW and its associated backoff number. Terminals then use this number (minus one) as an upper bound on a random uniform draw determining the number of frames to wait before attempting retransmission [DIS96].

An alternative protocol investigated in this study is to have the network terminal track for itself how many times each message has been unsuccessfully transmitted and set each message's backoff individually. For each additional retransmission, a counter (BACKOFF_NUMBER), which already exists in the standard, is incremented. To determine how many frames to delay before retransmission, the NT makes a uniform draw from 0 to ($2^{\text{BACKOFF\_NUMBER}}$-1). Thus each message is treated separately and the NCT is relieved of the burden of tracking ROW collisions.

4.2.7 Statistics Collection

Routines in the NTs and NCT instruct a statistics object to collect and report statistics for each iteration. This object updates a master statistics collection object at the end of each iteration. The master object then computes means, standard deviations, and confidence intervals for the parameters of interest. Output from each series of iterations is then imported into a spreadsheet for further comparisons.

Parameters are reported *only for channel requests that are actually served.* The simulation reports means, standard deviations, and confidence interval half widths for the following parameters:

- NT_Queue_Time for each priority level : The time from request generation at the NT to reception of the request at the NCT. Includes queueing time at the NT and transmission time.
- Overall_NT_Queue_Time: Aggregate of NT_Queue_Time over all priority levels
- NCT_Queue_Time for each priority level: the time the request spent queued for service at the NCT
- Overall_NCT_Queue_Time : Aggregate of NCT_Queue_Time over all priority levels
- Total_delay for each priority level: The time from service request generation to service establishment.
- Total_delay : Aggregate of Total_delay_for_priority over all priority levels
- Number_SCPC_Calls_Established for each priority
- Total_SCPC_Calls_Established : Aggregation of Number_SCPC_Calls_Established_for_Priority over all priorities
- Number_SCPC_Calls_Preempted for each priority: The number of calls preempted by higher priority calls
- Total_SCPC_Calls_Preempted: Aggregate of Number_SCPC_Calls_Preempted for each priority over all priority levels
- FOW_Loading: Proportion of FOW slots filled
- ROW_Loading: Proportion of ROW slots filled
- Mean_BW_Used : Bandwidth resource used
- Wtd_Mean_BW_used : Time weighted mean of bandwidth used
- Mean_Power_used: Power resource used
- Wtd_Mean_Power_used: Time weighted mean of power used

4.2.8 Verification

Because an object-oriented environment implements the simulation, assuring that the code functions as intended is easily accomplished as each object is implemented. Drivers

exercise each object having any substantial behavior (behavior other than just setting attributes). The Get's and Set's themselves are verified by examining attribute values before and after method invocation.

4.2.9 Validation

Assuring that that the results match expected values can only be done for the case of non-preemptive (with realignment also disabled) complete partitioning. Any algorithm that uses shared resources or any that enables preemption introduces interdependencies among the customer classes, hence the Erlang C formula does not apply. Only with basic complete partitioning is each class of customer served independently of any others, and thus amenable to queueing theory analysis. The following procedure validates the correct operation of the CP code:

- Write additional code in C++ to calculate the Erlang C probability of queueing value. This gives a more precise value than lookup in published tables [All90].
- Validate Erlang C calculation code against manual calculations and "convenient" cases in published tables--those whose probability of queueing and load level appear to be round numbers [All90]. For example, 22 servers handling an aggregate load of 15.8 Erlangs appears to result in a probability of queueing of 0.1, and the calculated value is 0.099748.
- Instrument the CP control terminal code to record whether each incoming call is immediately served or queued, and report summaries.
- Run test cases with a single NT sending a request every 1 second on average, with a frame duration of 0.73 sec. This eliminates contention for a ROW slot. The load varies with the mean call duration.
- Set number of channels (servers) to 23, mean call duration varied from a mean of 15 to 22 min. Selection of 23 servers allows preliminary correlation of results with

published tables [All90]. Runs with the full 200 duplex channels available result in the Erlang C formula being computationally intractable (for example, computing 199!).

- Take series of 15 iterations at each of the call durations with the statistics of the resulting queueing probability, computed as the proportion of calls queued upon arrival to the total of all arrivals, compared to the C++ code computed value.

Results are as follows:

Table 1. Validation Results

Load (Erlangs)	15	16	17	18	19	20	21	22
Measured Prob of Queueing								
99% CI Low	0.0263	0.0325	0.0441	0.0416	0.0091	0.1467	0.1664	0.5983
Mean	0.0924	0.0919	0.1407	0.1412	0.0817	0.3293	0.3682	0.7453
99% CI High	0.1586	0.1513	0.2374	0.2408	0.1544	0.5119	0.5700	0.8923
Erlang C Value	0.0380	0.0699	0.1193	0.1907	0.2883	0.4157	0.5757	0.7701

For all but the 19 and 21 Erlang loads, the Erlang C formula calculated values reside within a 99% confidence interval of the measured value. Further note that the 21 Erlang sample nearly is within 1% of residing in the 99% confidence interval. These discrepancies are attributed to the rather small sample size of 15. Given the above results, the call generation and request functions are judged to function correctly, as is the resource allocation.

4.3 Design of Experiment

This section briefly details the parameters varied, potential and actual measures of performance, and the method used to determine them.

4.3.1 Parameters that could be varied

The following constitute parameters that could have been varied in the investigation:

- Number of network terminals
- Homogeneity/types of network terminals
- Proportion of direct and NCT-routed SCPC communication
- SCPC communication bit rate
- ROW data (and therefore frame) rate
- Number of ROW channels
- FOW data rate (frame rate to match the ROW)
- Duration of simulated time
- Proportion of call requests in each priority category
- Allocation algorithm
- For algorithms that guarantee a minimum level of resource, the minimum level of resource for each priority category
- Call generation interarrival distribution and call length distribution
- Call destination distribution
- Power and bandwidth available
- Number of iterations

4.3.2 Scenario

This study acts out a rather limiting scenario, perhaps the communications during combat commencement. In general, the traffic contains a higher proportion of non-ROUTINE calls than normally seen. To stress the FOW and ROWs, only one of each is modeled. Link parameters are such that the satellite is assumed to operate in a less than

maximally efficient state. For example, earth coverage for the antennas is assumed instead of a narrow area coverage. Because this lowers the antenna's gain, fewer channels are supported. Also, while the DSCS III transponder #2 is reported to support 40 W output, a figure of 20 W is used [CDR78]. Many of the parameters' values are taken from the 1993 SHF-DAMA Draft Standard, Scenario Assumptions and Scenario #2 [DIS93]. A brief rationale for each parameter is listed below.

Parameters held constant defining this scenario include the following:

- Homogeneity/types of network terminals: All terminals are AN-TSC-100A's, maximum EIRP per DAMA circuit: 45 dBW. Maximum EIRP: 75 dBW. These parameters are specified in [DIS93]. The AN-TSC-100A is a common tactical terminal.
- Proportion of direct and NCT-routed SCPC communication: All SCPC traffic is direct NT-to-NT. This simplifies connection establishment without reducing the evaluation of the algorithms.
- Simplex/half and full duplex: All channels are symmetric full duplex--increases loading.
- SCPC communication bit rate: All SCPC channels communicate at 9600 bps. This is one of the highest specified in [DIS93] and therefore places higher demands on required bandwidth than lower bit rates.
- ROW data (and therefore frame) rate: 9600 bps, 0.73 sec/frame--a common frame duration per [DIS93]. Longer frame durations would result in more contention for the ROW channel, thus adversely adding another variable to the evaluation of the allocation algorithms.
- Number of ROW channels: 1. NT algorithms for determining which of available ROWs to use are not specified in [DIS96]. Using only one avoids the issue.
- FOW data rate (frame rate to match the ROW): 9600 bps, 0.73 sec/frame--a common frame duration per [DIS93].

- Duration of simulated time: 30.0 minutes. Nearly the maximum attainable with high loading levels and computer support available.
- Proportion of call requests in each priority category:

  ROUTINE: 25%

  PRIORITY: 50%

  FLASH: 20%

  FLASHOVERRIDE: 5%

  SYSTEM: 0%

  This distribution allows more than one level to be subject to preemption/reallocation, thereby more fully exercising the allocation algorithms.
- For algorithms that guarantee a minimum level of resource, the minimum level of resource for each priority category: The overall proportion of reserved resource is subdivided according to the call requests proportions. For example, with 100 units of resource running shared with minimum allocation and 20% shared, ROUTINE gets 100*(1-.2)*.25 = 20 resource units reserved, and can also compete for the 20 shared resource units.
- Call generation interarrival distribution: Poisson process with mean interarrival time of 30 sec. and exponential call duration with a mean of 3 min. This distribution is similar to those in [DIS93].
- Call destination distribution: Uniform over all NTs (other than the originating NT), per [DIS93].
- Power and bandwidth available for DAMA operation: 60 MHz bandwidth, 20W power, per [DIS93].

4.3.3 Simulation Factors

Listed below are the simulation factors, their domains, and a brief justification for their selection.

- Number of network terminals: 5, 10, 15, 20, 25, 30, 35, 40 ,45, 50, 55. This allows evaluation over a broad range of loads and location of stress points for each algorithm.
- Number of iterations: 10, 30. Computing capabilities do not allow 30 iterations for all loading levels for all algorithms while 10 is too few for valid comparison of measures of performance. Ten iterations give a general picture of performance. Therefore, complete sharing, complete partitioning, and sharing with minimum allocation using 40% shared are run with 30 iterations for a loading level representative of a moderate load for valid statistical comparisons.
- Preemption: disabled without moveable boundaries, enabled with moveable boundaries. Preemption without moveable boundaries is not investigated because it makes no sense to preempt a lower priority call when the lower priority has unused resource allocated.
- Allocation algorithm: CS, CP, and SMA with 0%, 20%, 40%, 60%, 80%, and 100% shared. The SMA with 0% and 100% are used for face validation of the CP and CS results.
- Backoff algorithm: SHF-DAMA specified and per message binary exponential. The binary exponential is not specified in the SHF-DAMA standard but provided an interesting side investigation.

4.3.4 Measures of Performance

The statistics collection subsection of this chapter for a full listing of data collected. The warfighter's primary concerns are connection establishment delay and maintaining a connection. Correspondingly, the primary measures of performance are the connection establishment delay and preemption probability. Because system efficiency is also important, another measure of performance is resource usage as manifested in the number of calls supported and the amount of power managed.

4.3.5 Statistical Considerations

4.3.5.1 Random Number Generation

Each set of iterations begins with the instantiation of a random number generator. This single generator is used for call interarrival times, destination and priority selection. The default seed is used. Because the calls are generated completely independently of the allocation algorithm, the same sequence of interarrival times, destinations, and priorities is guaranteed for each set of iterations. Thus, even corresponding iterations between allocation algorithms produce the same stochastic inputs. Because the same random number generator is used and not reset, each iteration within a series produces different stochastic inputs. Thus, each iteration uses independent, identically distributed inputs and produces an independent sample point to estimate an output distribution.

4.3.5.2 Warm-up Period/Steady State

For two reasons, a warm-up period is not included: to capture the transient behavior at system startup, and computational limitations on the duration of running high load levels.

4.3.5.3 Number of Iterations

From a numerical standpoint, this study ultimately involves comparing means of random samples. For this to be done in a statistically useful manner, at least 30 data points are required [All90]. Unfortunately, a full 30 runs for each of the various allocation algorithms at each loading level is not computationally feasible. Ten iterations are feasible and provide a general indication of the algorithms' performance. Thirty iterations are

undertaken for CP, CS and SMA with 40% of the resource shared, both for the SHF-DAMA specified backoff and the per-message binary exponential. SMA with 40% is selected because it shares nearly half the resource, while CS and CP share all and none, respectively.

4.4 Analysis and Results

This section analyzes results and draws conclusions about which algorithm best serves the SHF-DAMA architecture over the loads and configurations tested. Specific numerical comparisons are presented in the Section 4.4.2.4. Because the SHF-DAMA system will definitely include preemption, only results from the preemption-enabled algorithms are presented here. See Appendix A for availability of raw data of all the simulation runs, including those with preemption disabled.

4.4.1 Conclusions from Load-Varying Results

This section draws conclusions from the set of 10 iteration runs. For many load levels, this constituted the maximum number of iterations computationally feasible. Because the confidence intervals are large for this small number of runs, graphical comparisons are undertaken. To establish more precision in statistical comparisons, 30 iterations were undertaken for a single load level. Standard deviations for corresponding measures of performance between the 10 and 30 iteration runs differ by as much as 70% and typically by at least 15%. This indicates that increased iterations are warranted. Numerical results for the 30 iterations, single load level runs are presented in Section 4.4.2.4.

4.4.1.1 Examination of Call Setup Delay

Recall that call setup delay is the time difference between when an NT generates a request and when it receives a connection established message from the NCT. This includes NT queueing, transmission (and retransmission) time, queueing for resource at the NCT, and assignment transmission time by the NCT. Figure 6 summarizes this delay across allocation algorithms and load levels (each NT produces 6 Erlangs load):

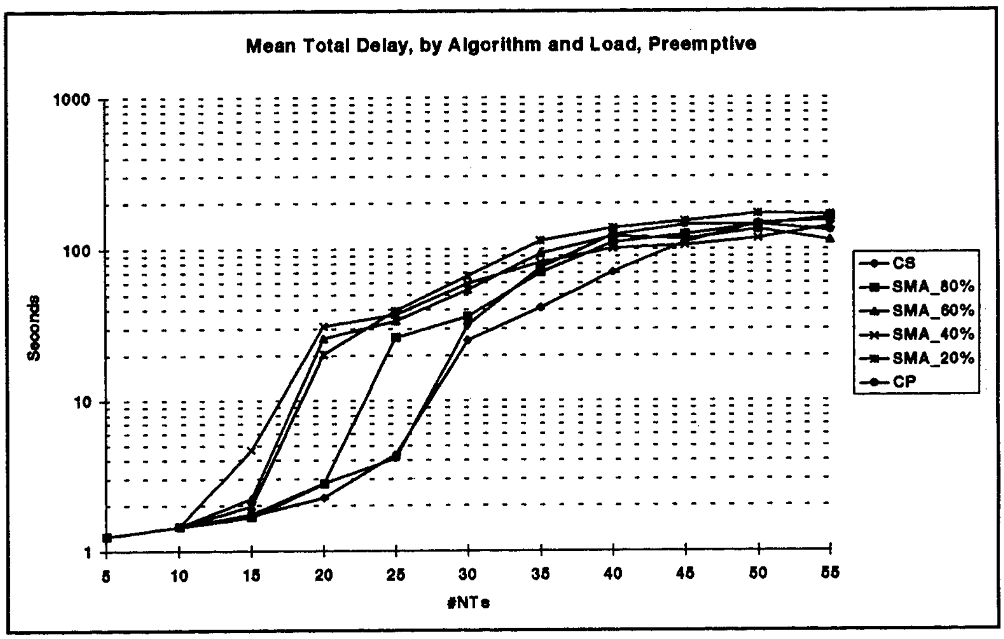

Figure 6. Mean Total Delay by Algorithm and Load, Preemptive.

Notable points evident in Figure 6 include the following:

- The allocation algorithms produced different results. This is contrast to the hypothesis of Section 3.6.
- Each algorithm experiences a drastic increase in delay, but at different points. Those points are, in order of increasing shared proportion: 30, 20, 20, 20, 25, and 30 NTs.
- Algorithms at opposite ends of the spectrum of shared resource (CP at 0% shared, and CS at 100%) outperform those sharing nearly half the resource over much of the load range.

- The performance of CS and CP degrades more gracefully than others over the range 15-35 NTs.
- At and below the load imparted by 10 NTs, the allocation algorithms perform the same.

Operationally, one can imagine not wanting a establishment delay of, say, more than 1/4 minute. That being the case, it is clear from Figure 6 that selection of the allocation algorithm has a dramatic effect in the number of terminals supported given the 1/4 minute threshold. In fact, Figure 6 points out that any threshold above about two seconds would point to the advantage of a particular algorithm, CS, in terms of number of terminals supported.

4.4.1.2 Examination of Resources Used

Because the amount of bandwidth available far exceeds any required, only the power resource is examined. This is examined to determine the mean number of channels supported by the given power level. As Chapter 2 points out, the transponder transmits at full power regardless of how many channels it carries. In truth the entire amount of power resource is always used. However, different allocation algorithms manage this power differently and support different mean numbers of channels. It is the number of channels supported, then, that is taken as the measure of power used. Figure 7 summarizes the mean number of channels active across allocation algorithms and load levels.

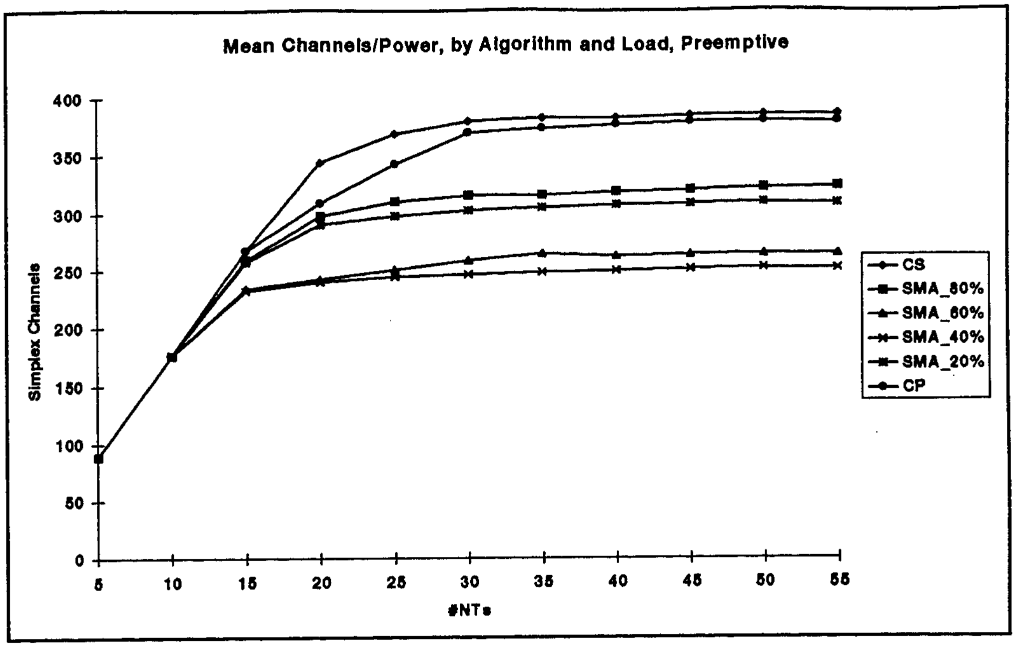

Figure 7. Mean Power Used.

Notable points evident in Figure 7 include the following:

- The allocation algorithms produced different results. This is contrary to the hypothesis of Chapter 3.
- Algorithms at opposite ends of the spectrum of shared resource (CP at 0% shared, and CS at 100%) outperform those sharing nearly half the resource over all of the load range. Note how strikingly algorithms sharing about half of the resource poorly manage the resource. In symmetric fashion those sharing significantly more and less than half of the resource managed it better, while those sharing all or none managed the resource best.
- The performance of CS and CP degrades more gracefully than others over the range 20-55 NTs. In particular, CS and CP continue to increase in mean resource used past the 25 NT level (150 Erlangs), while the others have basically leveled out.
- At and below the load imparted by 10 NTs, the allocation algorithms yield the same level of performance.

From these points is it concluded that either closing all resource to all competition or competing for the entire resource pool supports more NTs at high load levels.

4.4.1.3 Examination of Number of Calls Established

Examining the number of calls actually established is enlightening for comparison of the allocation algorithms as well. In particular, this comparison demonstrates how the performance of each algorithm degrades with increasing load. Figure 8 summarizes the number of calls established in 30 minutes of simulated time across allocation algorithms and load levels.

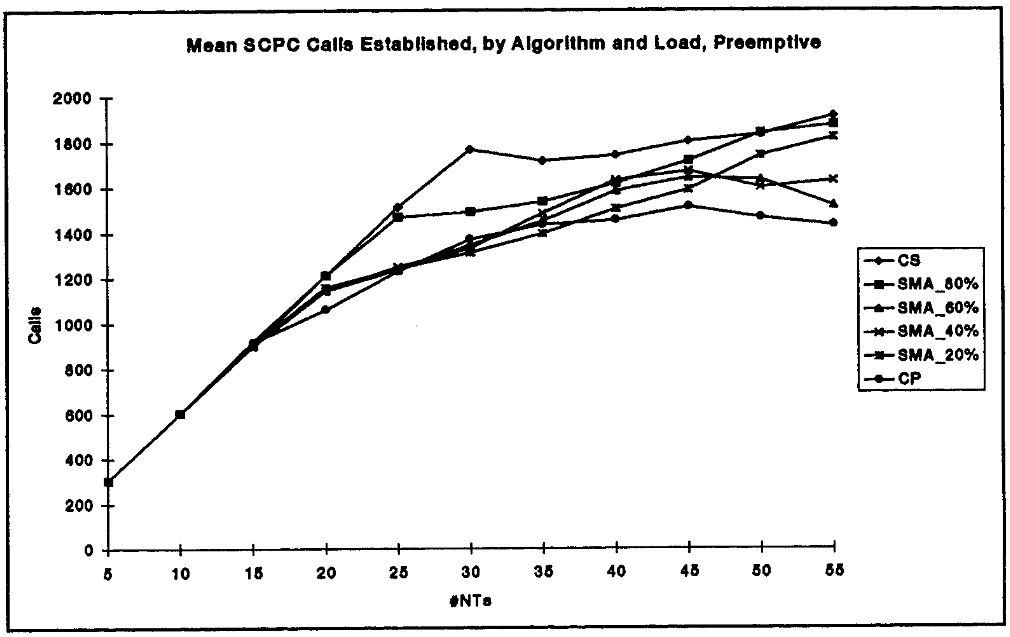

Figure 8. SCPC Calls Established.

Notable points evident in Figure 8 include the following:

- The allocation algorithms produced different results. This is contrary to the hypothesis of Chapter 3.
- With the exception of load levels (number of NTs) 30 and 35, algorithms at opposite ends of the spectrum of shared resource (CP at 0% shared, and CS at 100%) provide the worst and best performance.
- The general path of symmetrically opposed amounts of shared resource track reasonably parallel to each other. That is, CS tracks mostly with CP, SMA_20% with SMA_80%, and SMA_40% with SMA_60%.
- The algorithms that share more resource degrade in performance at higher load levels.
- At and below the load imparted by 10 NTs, the allocation algorithms perform the same.

From these observations, it is concluded that having a larger shared resource absorbs the fluctuations in call demands better than a small shared resource.

4.4.1.4 Examination of Number of Calls Preempted

The number of calls an algorithm preempts provides yet another interesting comparison. An efficient resource management algorithm establishes a maximal number of calls while preempting a minimal number. Figure 9 summarizes the number of calls preempted across allocation algorithms and load levels. Section 4.4.2.2 numerically examines the probability of preemption.

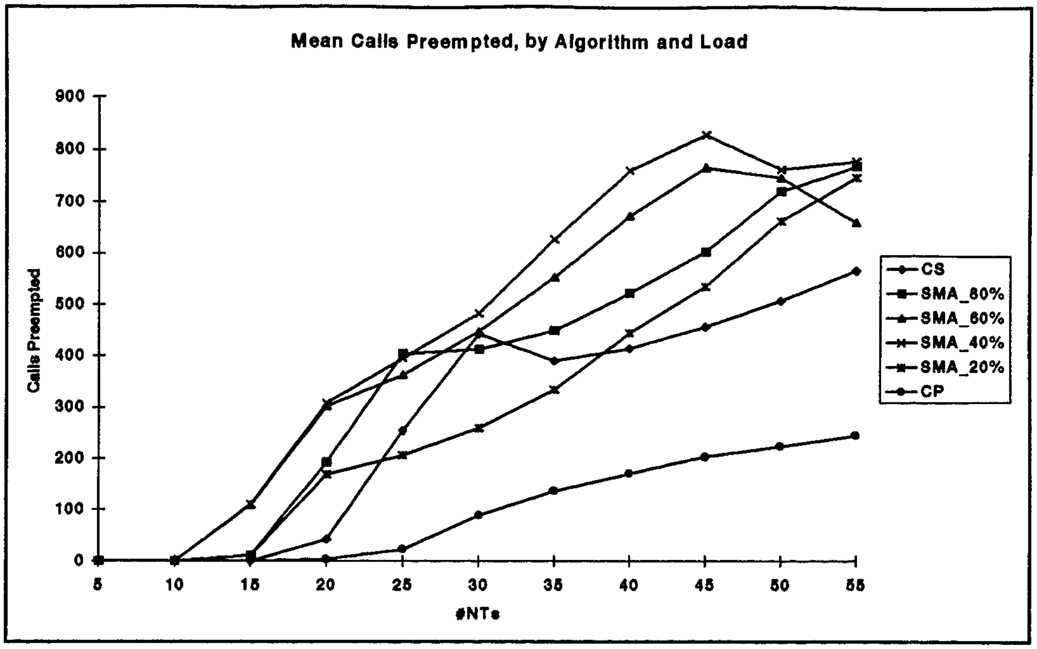

Figure 9. Calls Preempted.

Notable points evident in Figure 9 include the following:

- The allocation algorithms produced different results. This is contrary to the hypothesis of Chapter 3.
- Symmetric about the 50% shared level, the more (and less) resource shared produced dramatic reductions in preemption at higher levels. For example, at the 45 NT (270 Erlang) level, compared to CP, SMA_20% preempts 263% as much and SMA_40% preempts 406% as much. Similarly, compared to CS, SMA_80% preempts 132% as much and SMA_60% preempts 168% as much. Again, sharing about half the resource presents itself as a poor strategy.
- The general path of symmetrically opposed amounts of shared resource track parallel to each other. That is, CS tracks mostly with CP, SMA_20% with SMA_80%, and SMA_40% with SMA_60%. The exceptions are CS and SMA_80% peaking then dropping at higher levels.
- At and below the load imparted by 10 NTs, the allocation algorithms yield the same performance level.

4.4.1.5 Conclusions from General Observations

As evidenced by the performance of SMA_40% and SMA_60%, sharing nearly half the total resource inefficiently manages the resource. Connection establishment delays are higher, power is utilized inefficiently, fewer calls are established, and more are preempted. Instead, sharing all or none of the resource seems optimal. In fact, in all the above categories except the number of calls preempted, CS outperforms all others at moderate (15 NTs) to high (25 to 45 NTs) loads. In particular, it manages not less than 1.5% more power than the next-best alternative, and establishes not less than 15% more calls than the next-best alternative.

The high performance of the CP algorithm in the power used and calls preempted categories is attributed to perfect knowledge of the stationary traffic distribution with a corresponding allocation of resource. Recall from Section 4.3.2 that the resource boundaries are aligned perfectly with the traffic priority distribution. Whether this relative performance would remain as high in a nonstationary or non-perfectly matched traffic to resource proportion remains an open question.

Note also that CS is the simplest algorithm to implement. This is because there is no record keeping on a per-class basis, as there is with the other algorithms.

4.4.1.6 Comparison of Corresponding Results Using Binary Backoff

For completeness, this subsection briefly presents results from all the various categories explored for the standard backoff algorithm. Figure 10 summarizes the connection establishment delay:

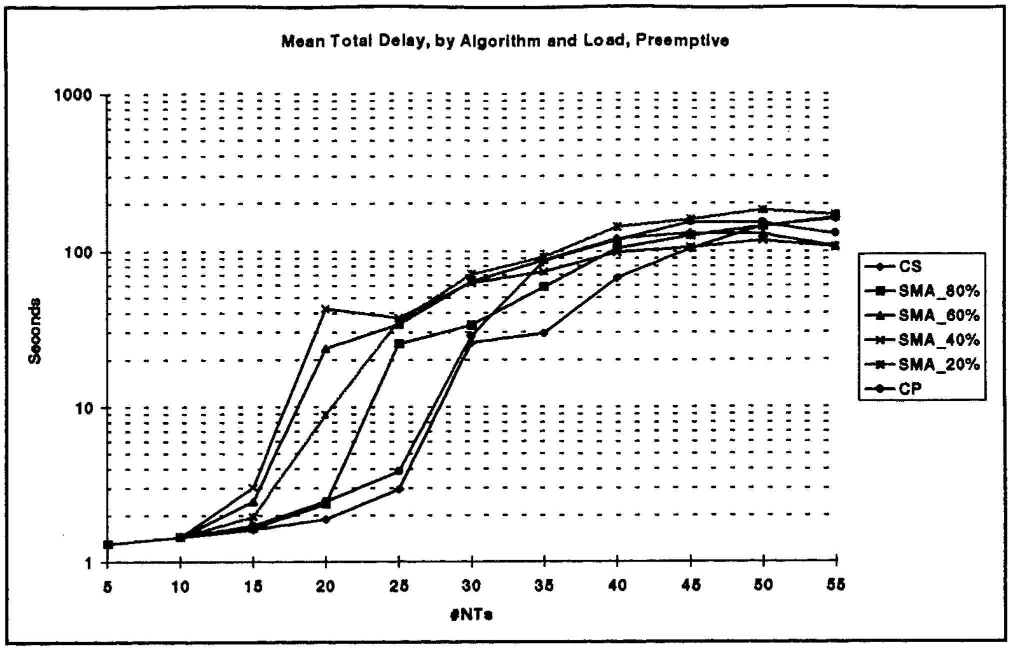

Figure 10. Call Establishment Delay, Per-message Backoff.

By comparison with Figure 6 it is evident that changing to a per message binary exponential backoff results in no great gain. Figure 11 displays how much relative gain (negative percentage) or loss (positive percentage) results from employing a binary exponential backoff. The range markings for each bin represent the lower cutoff point. For example, the bin labeled "0%" represents 0-5%.

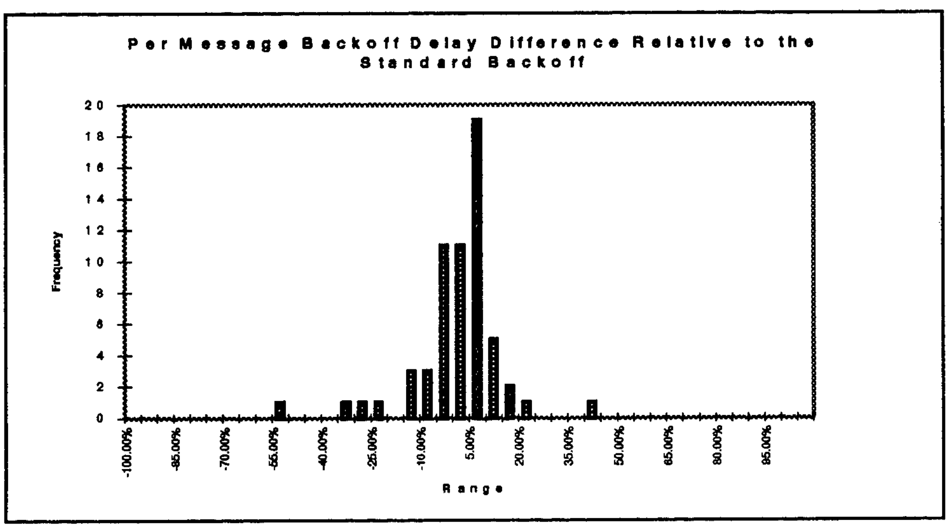

Figure 11. Per-Message Backoff Delay Difference Relative to the Standard Backoff.

As Figure 11 points out, switching to a binary exponential backoff results in no great gain. Twenty-two of the 66 algorithm-load combinations showed improvement or degradation of 5% or less, 44 of 66 show ±10% or smaller difference. Thus in terms of delay, the binary exponential backoff has no clear advantage.

A similar conclusion is drawn in Figures 12 and 13, detailing power usage:

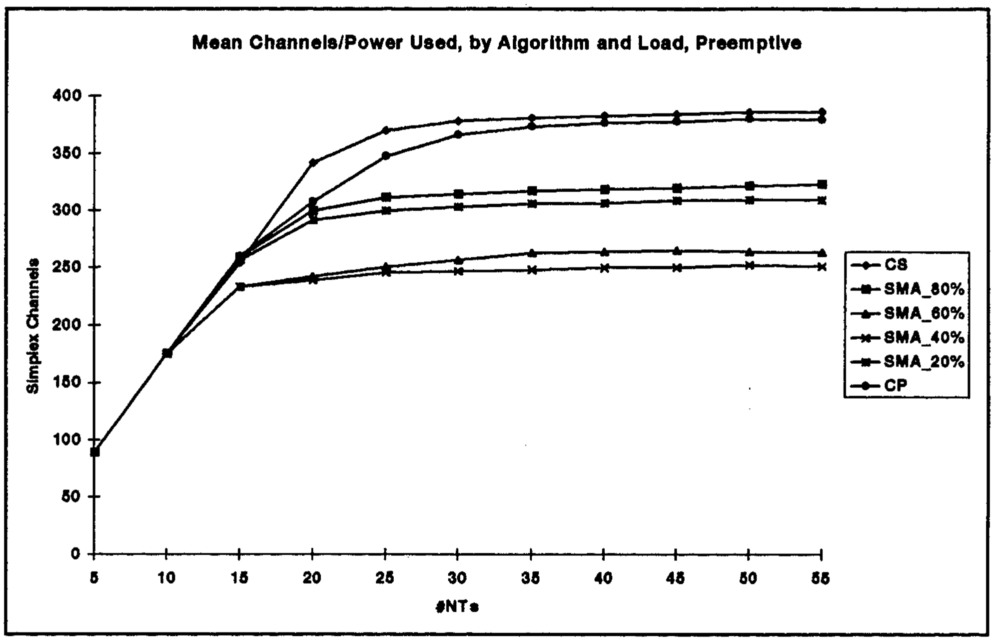

Figure 12. Mean Power Used, Per-message Backoff.

Again note the extreme similarity with the standard DAMA specified backoff algorithm, namely the grouping of the algorithms in pairs and their stacking. As with Figure 11, Figure 13 relates the relative difference between the per message and standard backoff.

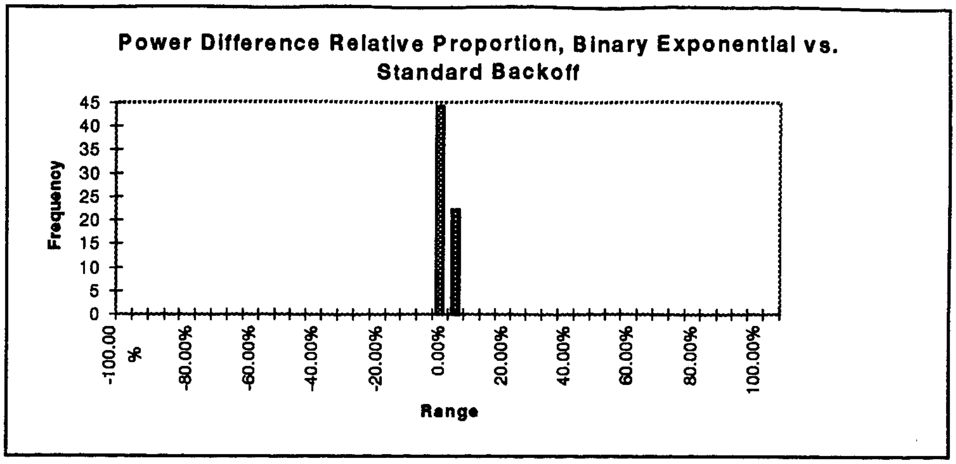

Figure 13. Per-Message Backoff Power Used Difference Relative to the Standard Backoff.

As Figure 13 points out, 2/3 of the algorithm-load combinations experience less than 5% gain in power used. The remaining 1/3 experiences 5-10% gain in power managed. Again, switching to a binary exponential backoff results in no great gain.

As related in Figure 14, the number of SCPC calls established follows a similar trend to Figure 8:

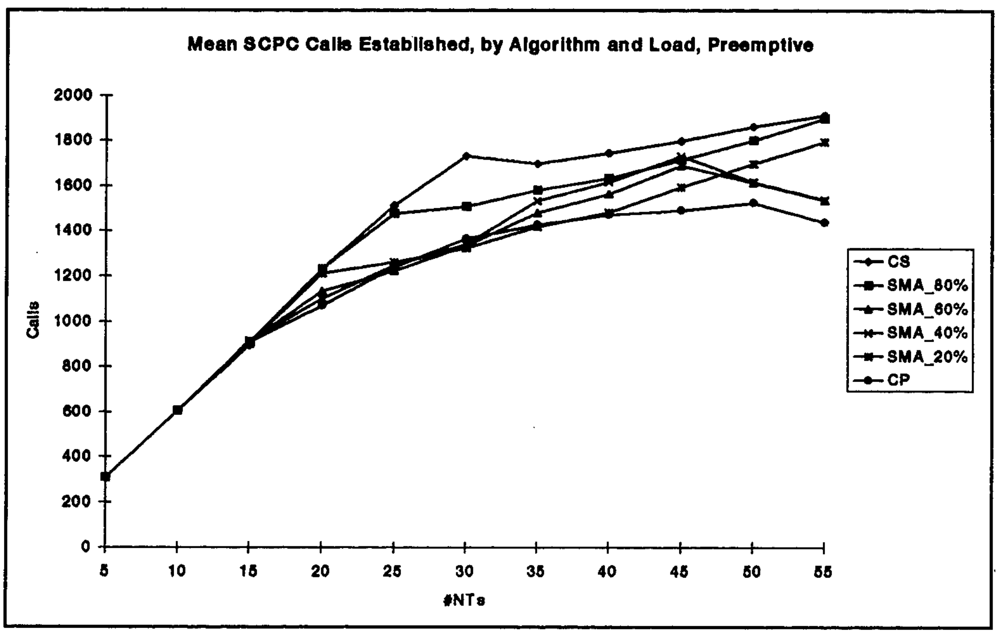

Figure 14. SCPC Calls Established, Per-message Backoff.

Again looking at the relative difference between the standard and binary exponential backoffs in Figure 15, no great gain is seen. All of the data points are within 10% of the corresponding point in the standard DAMA scheme.

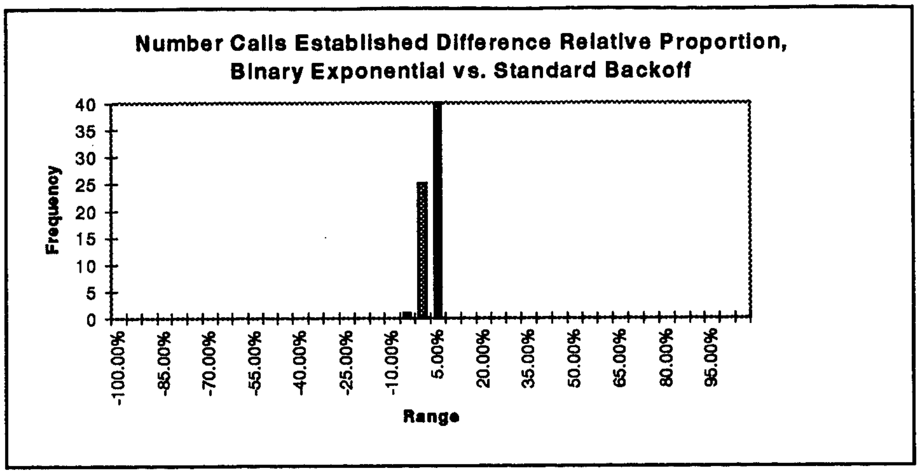

Figure 15. Per-Message Backoff Calls Established Difference Relative to the Standard Backoff.

Finally, Figure 16 shows the number of calls preempted:

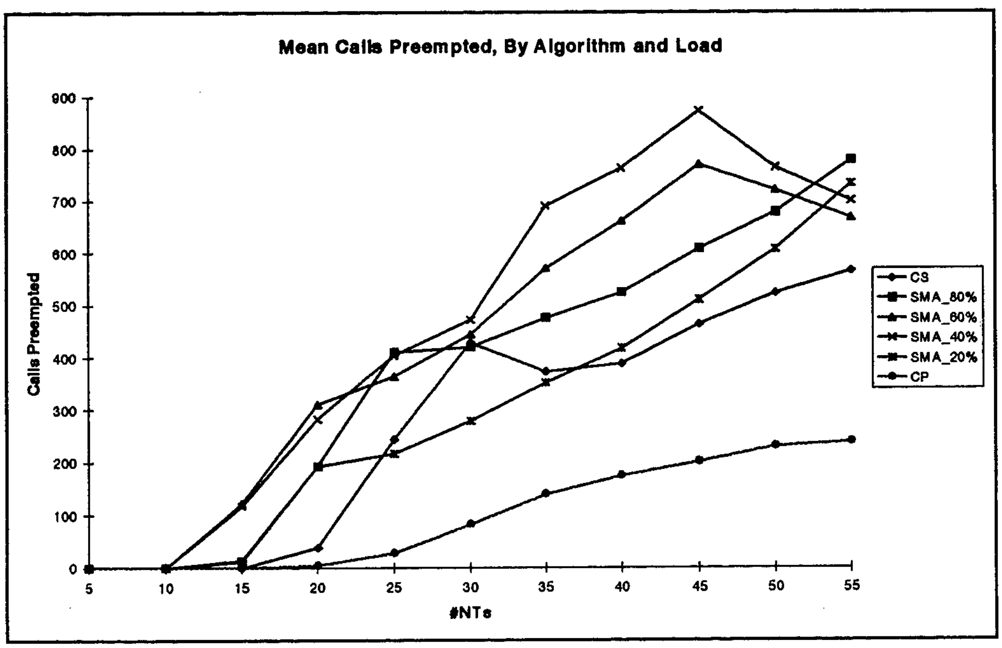

Figure 16. Calls Preempted, Per-message Backoff.

From Figure 17 below, note that 42 of the 66 algorithm-load combinations fall within 10% of their value for the standard DAMA backoff protocol. Again, no great advantage is gained by using the per-message binary exponential backoff.

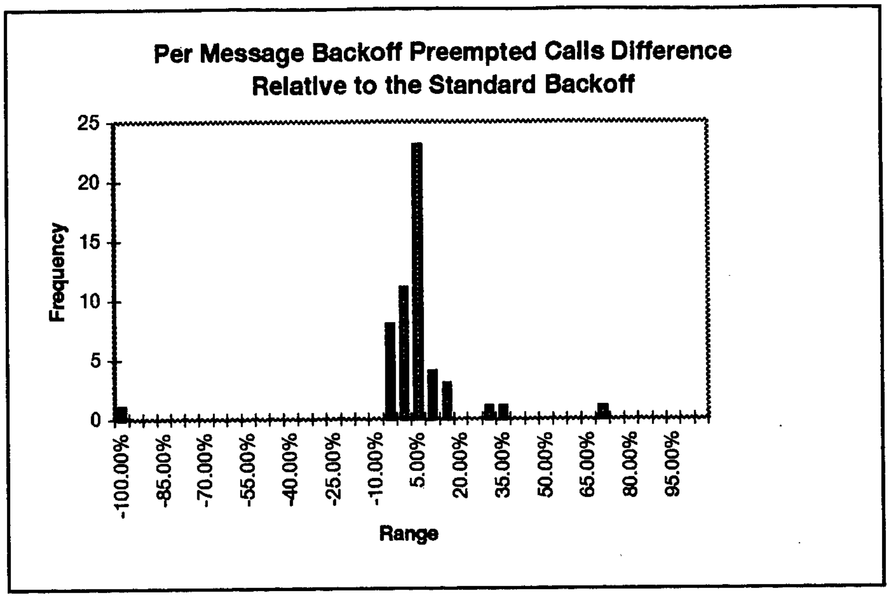

Figure 17. Per-Message Backoff Preempted Calls Difference Relative to the Standard Backoff

The conclusion from the above is that the per-message binary exponential backoff only adds complexity to the retransmission protocol. It does not consistently improve performance in terms of establishment delay, resource utilized, or number of calls established or preempted.

4.4.2 Conclusions from Increased Iterations

With the increase in the number of iterations comes a corresponding increase in the precision of the results. This section compares three allocation algorithms over a single load level, namely the 20 NT (120 Erlang) load. This load is examined because it is the lowest load at which the algorithms separate significantly in terms of performance.

4.4.2.1 Thirty Iteration Overview

The following charts present a quick overview of the measured performance in the same categories as examined in the previous section. Although only the 20 NT datapoint is presented, more information in the way of confidence intervals is present.

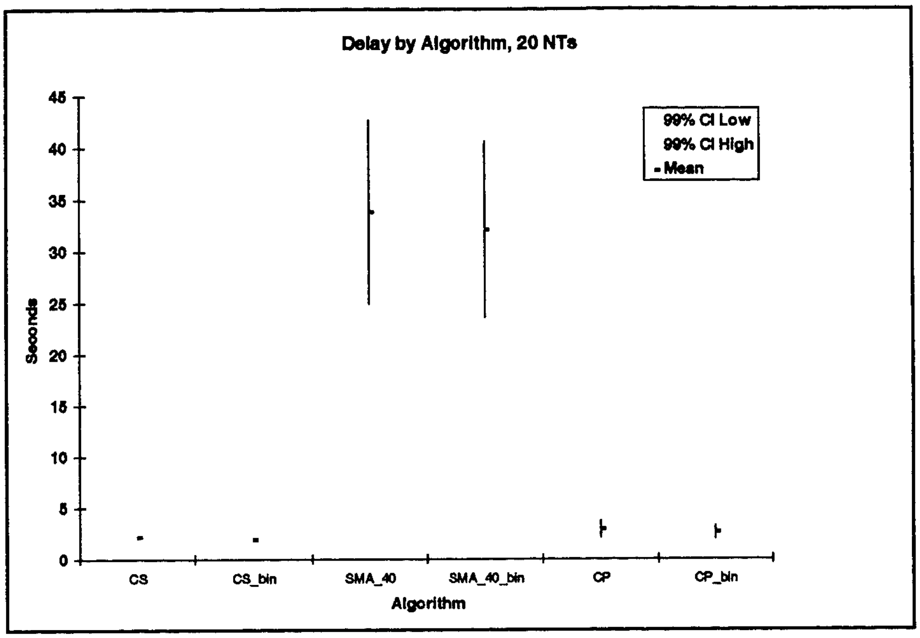

Figure 18. Call Establishment Delay, 20 NTs, 30 Iterations.

Note that not only does SMA_40% have a longer delay, the variance is much greater than CS and CP.

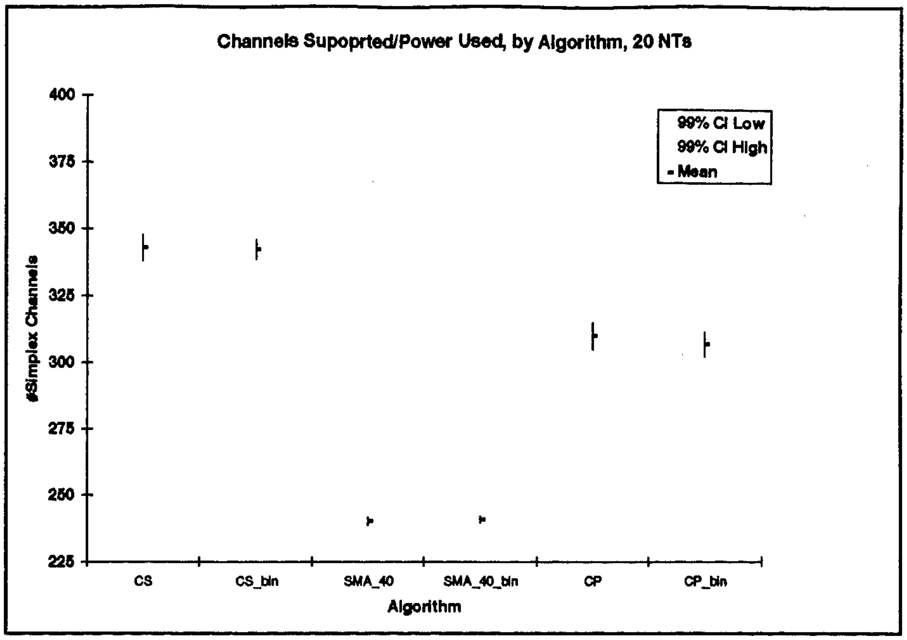

Figure 19. Power Used, 20 NTs, 30 Iterations.

Note that SMA_40% manages far less power than CS or CP.

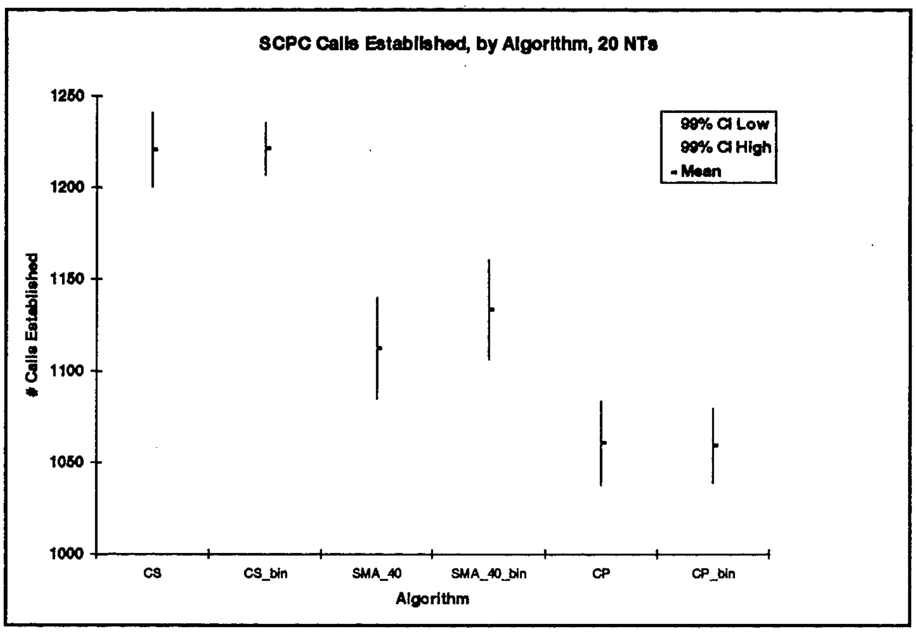

Figure 20. Calls Established, 20 NTs, 30 Iterations

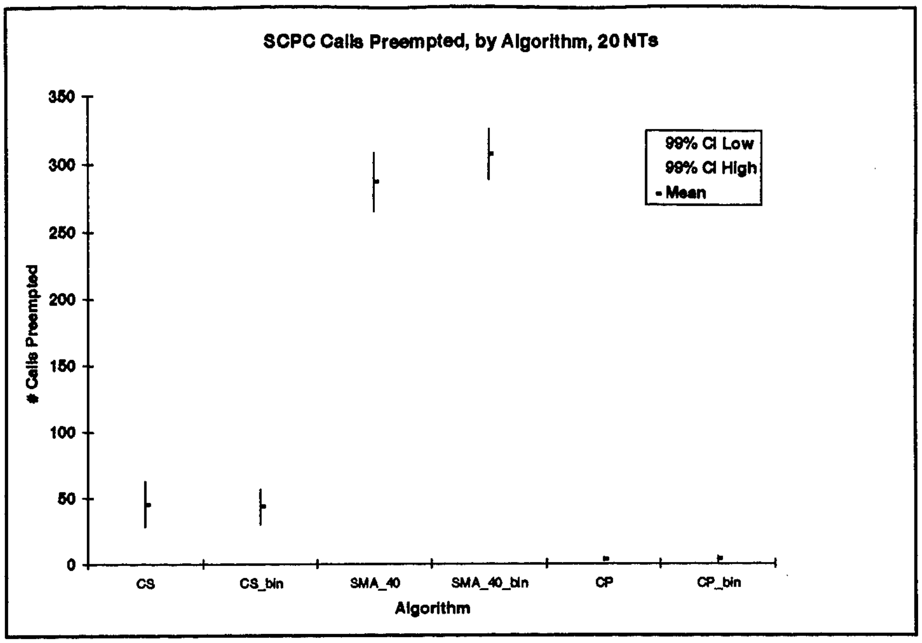

Figure 21. Calls Preempted, 20 NTs, 30 Iterations.

Note from Figure 21 that not only does CP preempt less, but it has a much smaller variance as well. Figure 22 gives insight into the mix of calls preempted by showing that SMA_40% not only preempted more calls, but preempted higher priority calls as well.

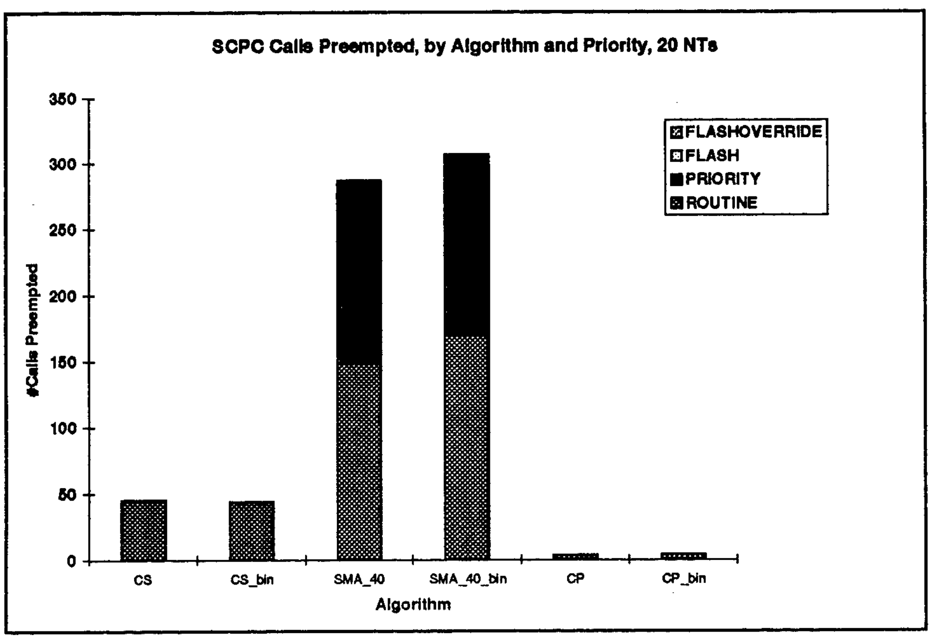

Figure 22. Preempted Call Mix, 20 NTs, 30 Iterations.

Specific numerical conclusions can be drawn and are presented in Section 4.4.2.4. General conclusions from only these carts include:

- Again, sharing nearly half the resource results in inefficient resource allocation. Sharing all or none results in lower delays, better power utilization, and fewer calls preempted.
- Sharing nearly half the resource manages the resource so poorly that higher level calls are preempted, whereas the extremes of sharing (CP, CS) do not.

4.4.2.2 Thirty Iteration Detailed Comparison, Absolute Differences

As was pointed out earlier in this chapter, this study ultimately involves the comparison of the means of random samples. While the data presented thus far provide a good review of the algorithms' performance, only with a numerical comparison is this possible. This section presents such an analysis.

The analysis follows the two sample test of means procedure of [All90]. Briefly, this involves computing a statistic from the sample means, standard deviations, and sizes, and a postulated difference in the means and comparing this statistic to $t_{n-1,\alpha}$, a critical value from the Student-t distribution. For each pair of algorithms compared, the postulated difference is modified such that the test statistic matches the desired $t_{n-1,\alpha}$. The reported postulated difference then tells which algorithm faired better and by how much, at the $\alpha = 0.01$ level. Setting the level of confidence at $\alpha = 0.01$ provides a high degree of certainty in the reported differences. The following tables summarize the absolute and relative results and are read as "(row algorithm) has measure of performance (value) different from (column algorithm)." For example, in the Table 2, note that the CS algorithm has a mean delay

39.007 seconds *less* than SMA with 40% shared. Similarly, SMA with 40% shared and a per-message binary backoff has a mean delay 22.12 seconds *more* than CP with the standard DAMA backoff.

Table 2. Establishment Delay Mean Absolute Difference (sec.), $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		0.1234	-39.0076	-36.9949	-1.4296	-0.9719
CS_bin			-39.2469	-37.2342	-1.6619	-1.2018
SMA_40				-8.4287	23.5824	23.8899
SMA_40_bin					22.1202	22.4282
CP						-0.5541
CP_bin						

Note also that the standard backoff to per-message binary exponential backoff comparisons show not more than 8.4 seconds improvement in delay. Further, in the case of CS, the per-message backoff increased delay. Similarly, for the power resource utilized:

Table 3. Power Use Mean Absolute Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-4.3161	98.4469	97.7905	27.1060	30.3255
CS_bin			98.7495	98.0979	27.1128	30.3580
SMA_40				-2.2199	-73.9896	-70.6990
SMA_40_bin					-73.3009	-70.0092
CP						-2.4677
CP_bin						

Again, CS improves over SMA_40% (by over 98 power units) and over CP (by at least 27 units). SMA_40% again proves inferior to CP by managing at least 70 units less. The standard backoff demonstrates a small (2.2 - 4.3) decrease in power utilized than the per-message backoff. Examining the number of SCPC calls established:

Table 4. Calls Established Mean Absolute Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-21.0218	80.3003	58.7404	134.8050	137.7748
CS_bin			83.4749	61.9018	138.3281	141.5379
SMA_40				-53.7932	21.8662	24.5861
SMA_40_bin					43.1787	45.8927
CP						-24.0404
CP_bin						

As before, CS improves over SMA_40%, by at least 62 calls and over CP by 135 calls, when comparing similar backoff algorithms. SMA_40%, however, does establish more calls than CP, by at least 22. The standard backoff proves inferior to the per-message backoff in each case. Looking at the number of calls preempted:

Table 5. Calls Preempted Mean Absolute Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-16.0044	-263.6640	-281.8725	27.5175	27.1939
CS_bin			-263.5167	-281.5556	29.1081	28.7666
SMA_40				-43.3336	265.0846	264.7720
SMA_40_bin					287.0551	286.7362
CP						-2.1808
CP_bin						

In this category, CS drastically improves over SMA_40% (by at least 264 calls), and improves over CP (by about 28 calls) SMA_40% again proves inferior to CP. In this category, the standard backoff improves over the per-message backoff.

The probability of a call being preempted must be presented as a range of values due to the stochastic nature of the results. The lower bound is calculated by taking the lower bound of the mean number of calls preempted and dividing by the upper bound of the mean number of calls established. The upper bound for the preemption probability is calculated in an analogous manner. Table 6 displays these values.

Table 6. Preemption Probability Calculation.

	Calls Established		Calls Preempted		Preemption Prob	
99% CI	Low	High	Low	High	Low	High
CS	1200.47	1241.06	28.08	62.38	2.26%	5.20%
CS_bin	1207.07	1235.46	30.39	56.41	2.46%	4.67%
SMA_40	1084.62	1139.65	264.93	307.54	23.25%	28.35%
SMA_40_bin	1106.42	1160.71	287.73	324.40	24.79%	29.32%
CP	1037.60	1083.53	2.25	4.68	0.21%	0.45%
CP_bin	1038.98	1079.49	1.77	5.70	0.16%	0.55%

4.4.2.3 Thirty Iteration Detailed Comparison, Relative Differences

While examining the above absolute differences is useful, examination of the relative differences is also enlightening. Appropriately, Tables 7-12 relate the same measures of performance as Tables 2-6, but in relative rather than absolute terms. Discussion of the data is postponed until after Table 12. The reader is cautioned against interpreting the table backwards. Recall that if X is Y% greater relative to Z, Z is *not* Y% less relative to X. First looking at the call establishment delay:

Table 7. Establishment Delay Mean Relative Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		6.51%	-115.35%	-115.32%	-49.66%	-37.60%
CS_bin			-116.06%	-116.07%	-57.73%	-46.50%
SMA_40				-26.27%	819.22%	924.28%
SMA_40_bin					768.43%	867.73%
CP						-21.44%
CP_bin						

Next, examining the mean power used/circuits established:

Table 8. Power Use Mean Relative Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-1.26%	41.00%	40.62%	8.75%	9.88%
CS_bin			41.13%	40.74%	8.75%	9.89%
SMA_40				-0.92%	-23.87%	-23.04%
SMA_40_bin					-23.65%	-22.81%
CP						-0.80%
CP_bin						

Next examining the number of SCPC circuits established:

Table 9. Calls Established Mean Relative Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-1.72%	7.22%	5.18%	12.71%	13.01%
CS_bin			7.51%	5.46%	13.04%	13.36%
SMA_40				-4.75%	2.06%	2.32%
SMA_40_bin					4.07%	4.33%
CP						-2.27%
CP_bin						

Looking at the number of calls preempted:

Table 10. Calls Preempted Mean Relative Difference, $\alpha = 0.01$

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-36.88%	-92.12%	-92.10%	793.77%	728.41%
CS_bin			-92.06%	-91.99%	839.66%	770.53%
SMA_40				-14.16%	7646.67%	7092.11%
SMA_40_bin					8280.43%	7680.43%
CP						-58.41%
CP_bin						

Finally, examining the preemption probability, recall that this must be done twice to account for the upper and lower bounds of the number of calls preempted and the number of calls established. Accordingly, Table 11 compares the relative differences of the lower bounds of preemption probability and Table 12 compares the upper bounds.

Table 11. Relative Difference in Lower Bound Preemption Probabilities

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		-8.02%	-90.27%	-90.87%	990.37%	1279.35%
CS_bin			-89.42%	-90.08%	1085.49%	1399.68%
SMA_40				-6.22%	11102.14%	14071.01%
SMA_40_bin					11845.40%	15011.25%
CP						26.50%
CP_bin						

Table 12. Relative Difference in Upper Bound Preemption Probabilities

	CS	CS_bin	SMA_40	SMA_40_bin	CP	CP_bin
CS		11.21%	-81.67%	-82.28%	1050.98%	847.93%
CS_bin			-83.52%	-84.06%	934.98%	752.40%
SMA_40				-3.29%	6180.01%	5072.13%
SMA_40_bin					6393.90%	5248.28%
CP						-17.64%
CP_bin						

4.4.2.4 Thirty Iteration Conclusions/Overall Conclusions

From the Tables 2-12, it is clear that complete sharing dominates as the best performer. Comparing per-message backoff algorithm against per-message backoff and standard backoff against standard backoff, CS reduces delay over CP by a minimum of 46.5% (1.2 sec.), and over SMA_40% by a minimum of 37 seconds. The apparent anomaly of 115% reduction in establishment delay as compared to SMA_40% is attributed to the high variance of SMA_40% and the low corresponding delay figure for CS. To process its calls, similarly corresponding versions effectively manage a minimum of 8.75% (27 channels) worth of power more than CP and 40.7% (98 channels) worth more than SMA_40%. These occur as CS processes a minimum of 12.7% (134 calls) more calls than CP and a minimum of 5.5% (61 calls) more than SMA_40%. In terms of

preemption, CS does preempt more than CP (a minimum of about seven times as much, or 27 calls), but drastically less than SMA_40% (at least 92%, or 263 calls). Looking at preemption probability, CS outperforms SMA_40% by at least 82%. SMA_40% in turn performs far worse than CP, having a preemption probability at least fifty times as much. While CS's preemption probability is about eight times as much as CP's, the absolute numbers show that CS preempted about 32 to CP's 4. Thus preemption difference is not as great as a factor of eight might imply.

In terms of the standard backoff versus the per-message binary exponential backoff, the data above point to a disadvantage for the standard backoff in the areas of power used (at least 0.8%) and calls established (at least 1.7%). Comparisons for preemptions and delay are inconclusive. Overall, the additional complexity of the per-message protocol is not warranted.

4.5 Chapter Summary

This chapter presents details of the experiment design, conduct, and results. Summary data are presented with full more full details in the appendices. See Appendix A for raw data availability.

5. *Summary*

5.1 Summary/Conclusion

This chapter summarizes this effort, restates overall conclusions from Chapter 4, highlights contributions of this work and outlines areas for further research. The reader is referred to Section 4.4.2.4 for specific numerical results.

5.1.1 Investigation Summary

This work investigates the potential performance of the proposed SHF-Demand Assigned Multiple Access (SHF-DAMA) system. Limited to consideration of direct network terminal (NT)-to-NT single-channel-per-carrier (SCPC) traffic, the call establishment delay, power usage, number of calls connected and preempted are presented over a range of load and resource allocation algorithms. The central network control terminal (NCT) implements complete sharing (CS), complete partitioning (CP), and sharing with minimum allocation (SMA) algorithms to manage the transponder's power and bandwidth resources.

Results from computer simulation of the system are used to make a recommendation as to the allocation algorithm best suited for implementation in the SHF-DAMA system.

5.1.2 Conclusions Restatement

It is clear that complete sharing dominates as the best overall performer. Comparing per-message backoff algorithm against per-message backoff and standard backoff against

standard backoff, CS improves over CP and over SMA with 40% shared. To process its calls, similarly corresponding versions use less power than CP and SMA_40%. These occur as CS processes more calls than CP and more than SMA_40%. In terms of preemption, CS does preempt more than CP, but drastically less than SMA_40%.

In terms of the standard backoff versus the per-message binary exponential backoff, the data point to a slight edge in terms of power usage and calls processed. Results for call establishment delay and preemption are inconclusive. Overall, the additional complexity of the per-message protocol is not warranted.

5.1.3 Contributions of This Work

Perhaps most importantly, this work develops a portable simulation code for investigation of the expected performance of the proposed SHF-DAMA satellite communications system. Next, this work sheds light onto the expected performance of the SHF-DAMA system under a stressing scenario over various resource allocation algorithms, preemption options, and retransmissions protocols. Finally, this study introduces the concept of resource usage boundary realignment on a per-request basis.

5.1.4 Potential for Future Work

This study investigated only a single scenario. A great deal of potential exists in investigation of other scenarios and increased functions of the proposed SHF-DAMA system. The following subsections introduce potential extensions of this work.

5.1.4.1 Non-uniform Network Terminals

The scenarios defined in [DIS93] indicate a mix of network terminals. This mix should be introduced into the scenario. Infrastructure is already in place to allow different terminal types.

5.1.4.2 Account for Modem Bank

This investigation assumes that ports at the originating and terminating terminals are available. Because this study examines the NCT's resource allocation algorithms, including a measure of end-user blocking only obscures the algorithms' performance. To characterize the overall system performance with more fidelity, however, end-user blocking should be accounted for. Again, the model infrastructure is already in place to accommodate this, specifically the NT database tracks which terminals have what modems available.

5.1.4.3 Add Data Transmission

While this study focuses on SCPC communications, the SHF-DAMA system will support packet transmission as well. Modeling this capability will place a higher load on the ROW and certainly on the FOW/OCOMM channels. How this will effect the establishment of SCPC connections is unknown.

5.1.4.4 Different Scenarios

The stressing scenario of this study constitutes only a single data point in the domain of possible scenarios. More scenarios should be investigated to give a larger picture of SHF-DAMA's likely performance.

5.1.4.5 Remove 4 CROW Message/Frame Restriction

While not a parameter of this investigation, restricting a network terminal to four opportunities to compete for a contention Return Orderwire slot may well effect performance. This possibility warrants investigation. Again, this is easily accomplished with small modifications to the existing simulation code.

5.1.4.6 Introduce Intermod Products and Algorithms to Overcome

As recounted in Chapter 2, intermodulation products significantly reduce the resource available for allocation. Algorithms such as those cited in Chapter 2 should be investigated. This would require that specific units of resource be allocated, which is not currently done.

5.1.4.7 Include the 30 Second Voice Preemption Delay

The SHF-DAMA standard specifies that SCPC voice circuits will receive an audible tone for 30 seconds before the circuit is terminated due to preemption [DIS96]. This investigation accounted only for data traffic not requiring the 30 second delay. This immediately freed resources. The investigator believes that including the voice preemption delay would significantly effect resource utilization and warrants investigation.

5.2 Chapter Summary

This chapter presented primary results from this study. The interested investigator can contact Dr. Richard A. Raines at the USAF Air Force Institute of Technology for further details, including source code and raw data availability.

Appendix A. *Source Code and Raw Data Release Information*

Further information concerning the MODSIM II and C++ code developed for this investigation can be obtained by contacting Captain Richard A. Raines in the Department of Electrical and Computer Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, 45433. Raw data in ASCII format and summarized data in Microsoft® Excel™ 5.0 format are also available.

Appendix B. *Link Analysis and Budget*

		Uplink			Downlink			
Satellite Transmitter power (dB)					13.0103	20	W	MBA:
Satellite Transmit antenna gain (dBi)					15	31.62		EC = 15
								NC = 26
EIRP (dBW)		70.5			28.0103	632.5		
Max EIRP per DAMA channel		45						
Number terminals		20						
Active channels per terminal		20						
EIRP per channel per terminal		45						
Transponder power dedicated to each circuit (dBW)					-1.25717	0.749		
Transponder power dedicated to other circuits (dBW)					24.7526	298.7		
Transponder power dedicated to noise (dBW)					25.2243	333		
Free space loss (dB)		-202.2			-201.4			
Margin (dB)		-3			-3			
Receiver antenna gain (dBi)		14.4			50.4	TSC-100A		EC = 14.4
								NC = 29.4
Received power per link (dBW)		-145.8			-155.257			
Receiver Noise								
Bandwidth (dB-Hz)	77.78		6E+07	77.7815		6E+07		
Boltzmann's const (dBW/k-Hz)	-228.6			-228.6				
Temperature (dBK)	31.5			24.5939		288		
Noise power density (dBW/K)	-197.1			-204.01				
Noise Power (dBW)		-119.318			-126.225			
Number simplex channels		400						
Transponder gain (state)	6	116.2	140					
Total power @ TX antenna input (dBW)		-0.33253						
Ratio dedicated to each link		0.00118						
Ratio dedicated to all links		0.47349						
Ratio dedicated to noise		0.52651						
Pr/N		-26.4815			-29.0326			
Overall Pr/N					-30.952			
Pr/No		51.3			48.7489			
Overall Pr/No					46.8295			
Data rate					39.8227	9600		
Required Eb/No					7			
Margin					0.00676			
Assumptions: Full duplex channels; uniform terminals, 9600 bps channel; TSC-100A terminal, earth coverage								

Abr92. Abramson, Norman, "Fundamentals of packet multiple access for satellite networks," *IEEE Journal on Selected Areas in Communications*, Vol. 10, No. 2, February 1992, pp. 309-316.

Aei78. Aein, J.M., "A multi-user-class, blocked-calls-cleared, demand access model," *IEEE Transactions on Communications*, Vol. COM-26, No. 3, March 1978, pp. 378-385.

AeK76. Aein, Joseph M. and Kosovych, Ostap S., "On capacity allocation strategies for DoD communications satellites," Report ADA030796. Fort Belvoir: Defense Technical Information Center, 1976

AeK77. Aein, Joseph M. and Kosovych, Ostap S., "Satellite capacity allocation," *Proceedings of the IEEE*, Vol. 65, No. 3, March 1977, pp. 332-342.

All90. Allen, Arnold O., *Probability, Statistics, and Queueing Theory with Computer Science Applications*, San Diego, CA, Academic Predd, Inc., 1990.

AiB90. Aicardi, M., Bolla, R., and Minciardi, R., "Optimization of capacity allocation among users and services in integrated networks," *Proceedings of the International Conference on Communications-ICC 90*, Vol. 2, 1990, pp. 302.3/1-7.

BaB82. Barberis, Giulio, and Brignolo, Roberto, "Capacity allocation in a DAMA satellite system," IEEE Transactions on Communications, Vol. COM-30, No. 7, July 1982, pp. 1750-1757.

Bin81. Binder, R., in Kou, Franklin F., "Packet protocols for broadcast satellites," in *Protocols and Techniques for Data Communication Networks*, Englewood Cliffs, NJ: Prentice-Hall, 1981.

CDR78. CDRL-A041, "DSCS III Satellite Engineer's Handbook," 3rd Space Operations Squadron, AFSPC, Falcon AFB, CO, 1978.

DIS93. Defense Information Systems Agency, *SHF-DAMA Standard (Draft)*, Fort Monmouth, NJ, May 1993.

DIS96. Defense Information Systems Agency, *Interoperability and Performance of Non-EPM SHF SATCOM Link Control Protocols and Messaging*, MIL-STD-188-186, Fort Monmouth, NJ, April 1996.

DoP94. Doyle, G., and Pitts, C., "A Demand Assigned Multiple Access(DAMA) prototype implementation," *IEEE MILCOM Conference Record*, 1994, Vol. 3, pp. 972-976.

Fre74. Frenkel, Gabriel, "The grade of service in multiple-access satellite communications systems with demand assignments," *IEEE Transactions on Communications*, Vol. COM-22, No. 10, October 1974, pp. 1681-1685.

HoL79. Horstein, Michael, and LaFlame, David T., "Multilevel SCPC system design," *IEEE Transactions on Communications*, Vol. COM-27, No. 10, October 1979, pp. 1441-1448.

Irl78. Irland, Marek, I., "Buffer management in a packet switch," *IEEE Transactions on Communications*, Vol. COM-26, No. 3, March 1978, pp. 328-337.

JoR88. Joseph, Kuriacose, and Raychaudhuri, Dipankar, "Simulation models for performance evaluation of satellite multiple access protocols," *IEEE Journal on Selected Areas in Communications*, Vol. 6, No. 1, January 1988, pp. 210-222.

KaK80. Kamoun, Farouk and Kleinrock, Leonard, "Analysis of shared finite storage in a computer network node environment under general traffic conditions," *IEEE Transactions on Communications*, Vol. COM-28, No. 7, July 1980, pp. 992-1003.

Kau81. Kaufman, Joseph, S., "Blocking in a shared resource environment." *IEEE Transactions on Communications*, Vol. COM-29, No. 10, October 1981, pp. 1474-1481.

KoL95. Ko, Sung Chan, Lee, Sang Mun, and Choi, Hyung Jin, "A new channel assignment algorithm for reducing IMPs in one-level SCPC satellite systems," *IEEE Transactions on Communications*, Vol. 43, No. 2, February-March 1995, pp. 1046-1054.

Lab85. Laborde, Enrique, "Optimization of demand assigned SCPC satellite networks," *Space Communication and Broadcasting*, Vol. 3, No. 3, pp. 201-206.

MaJ75. Marks, Barry I., Janc, Robert V., and Thomopoulos, Nick T., "A preemptive radio net queueing model," *IEEE Transactions on Communications*, Vol. COM-23, No. 11, November 1975, pp. 1311-1315.

Mar86. Maral, Gerard, *Satellite Communication Systems*, Great Britain, John Wiley and Sons Ltd., 1986.

McJ85. McDysan, David, and Jabbari, Bijan, "A performance model for satellite capacity demand assignment, with DSI," *Proceedings of the IEEE International Conference on Communications-ICC 85*, Vol. 1, 1985, pp. 8.8/1-8.

MeG92. Mese, E. Dalle, Giordano, S., Berizzi, F., Pinizzotto, A., and Pinto, R., "Design analysis of a satellite SCPC-DAMA VSAT network," *Communications on the Move. Singapore. ICCS/ISITA '92*, Vol. 2, November 1992, pp. 471-475.

NgS90. Nguyen, Thieu and Suda, Tatsuya, "Survey and evaluation of multiple access protocols in multimedia satellite networks," *Proc. IEEE: SOUTHEASTCON '90*, Vol. 2, April 1990, pp. 408-413.

OkY82. Okinaka, Hideo, Yutaka, and Hirata Yasuo, "Optimum frequency assignment for satellite SCPC systems," *Proceedings of the International Conference on Communications-ICC 82*, Vol. 1, 1982, pp. 2E.3/1-10.

PeM92. Petr, David W., Murthy, K. M., Frost, Victor S., and Neir, Kyn A., "Modeling and simulation of the resource allocation process in a bandwidth-on-demand satellite communications network," *IEEE Journal on Selected Areas in Communications*, Vol. 10, No. 2, February 1992, pp. 465-477.

Qua77. Quarta, P., "SCPC: System philosophy and potential advantages in satellite communication for developing countries," *EUROCON '77 Proceedings on Communications*, 1977, pp. 550-557.

RaB80. Rappaport, Stephen S., and Bose, Sanjay, "Demand assigned multiple access systems using collision type request channels: Stability and delay considerations," *NTC '80. Proceedings of the IEEE 1980 National Communications Conference*, 1980, pp. 59.2/1-5.

Rai96. Raines, Richard A., Class notes from the course "Computer communications networks," Air Force Institute of Technology, 1996.

Rap79. Rappaport, Stephen S., "Demand assigned multiple access systems using collision type request channels: Traffic capacity comparisons," *IEEE Transactions on Communications*, Vol. COM-27, No. 9, September 1979, pp. 1325-1331.

SaA94. Saadawi, Tarek N., Ammar, Mostafa H., Hakeem, Ahmed El, *Fundamentals of Telecommunication Networks*, New York, NY, John Wiley & Sons, Inc., 1994.

ScF84. Screenath, K., and Feher, Kamilo, "Comparison of SCPC and TDMA systems," *Proceedings of the International Conference on Communications-ICC 84*, Vol. 1, May 1984, pp. 595-598.

Skl88. Sklar, Bernard, *Digital Communications*, Englewood Cliffs, NJ, Prentice Hall Publishing Co., 1988.

Sta91. Stallings, William, *Data and Computer Communications, 3rd ed.*, New York, NY, Macmillan Publishing Co., 1991.

ThA84. Thareja, Ashok K., and Agrawala, Ashok K., "On the design of oprimal policy for sharing finite buffers", *IEEE Transactions on Communications*, Vol. COM-32, No. 6, June 1984, pp. 737-740.

TiS88. Tipper, D., and Sundareshan, M.K., "Adaptive policies for optimal buffer management in dynamic load environments," *Proceedings of IEEE INFOCOM '88*, 1988, pp. 535-544.

VuF85. Vuong, X. T., and Forsey, R. J., "Optimal carrier frequency assignments for a two-level SCPC system," *Proceedings of the IEEE International Conference on Communications-ICC 85*, Vol. 1, 1985, pp. 8.6/1-5.

WoG86. Wong, Kevin and Georganas, Nicolas D., "Strategies for optimal capacity allocations in DAMA satellite communications systems," *Computer Communications*, Vol. 9, No. 1, February 1986, pp. 26-32.

Vita

Captain Eric P. Hobson graduated from Michigan State University with a Bachelor of Science degree in Computer Science in 1991. A Distinguished Graduate from Air Force ROTC, he then attended Basic Communication Officer Training at Keesler AFB, MS. At his follow-on assignment at Space and Missile Systems Center, Los Angeles AFB, CA, he spent eighteen months in computer-communications systems acquisition. He then completed an internship with The Aerospace Corporation, a Federally Funded Research and Development Center, researching high speed networking and satellite ground system communications. In May, 1995, he entered the School of Engineering, Air Force Institute of Technology (AFIT). Following graduation from AFIT, he began work at the Air Force Wargaming Institute, Maxwell AFB, AL.

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Sponsored by DISA, the SHF-DAMA Standard addresses the warfighter's requirements for flexible, reliable, and efficient (technically and fiscally) satellite communications. The Standard proposes a system supporting both packet data transfer and single-channel-per-carrier voice and data circuits assigned on a demand basis. The Standard does not address management of the DSCS III transponder's bandwidth and power resources among priority classes of users.

This effort characterizes the SHF-DAMA system's performance over each combination of the following resource management algorithm features: preemption enabled and disabled; using the Standard-specified collision resolution technique and a binary exponential backoff; using complete partitioning, complete sharing, and sharing with minimum allocation strategies. The author introduces a novel algorithm for avoiding unnecessary preemption. A simulation written in MODSIM II collects the following measures of performance over a broad load range: call establishment delay, number of calls simultaneously supported, power used, and number of calls preempted.

The primary conclusion drawn using graphical and hypothesis testing methods is that the SHF-DAMA system should implement the complete sharing management algorithm. This algorithm reduces call setup time and most efficiently manages satellite resources. As a secondary conclusion, the binary exponential backoff proves to be not significantly better than the Standard-specified backoff.

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